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REDUCING LAUNCH OPERATIONS COSTS

NEW TECHNOLOGIES AND PRACTICES

A TECHNICAL MEMORANDUM

SEPTEMBER 1988

CONGRESS OF THE UNITED STATES
Office of Technology Assessment
Washington, DC 20510-8025

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Foreword

Reducing the costs and improving the reliability of space transportation are key to making more effective use of the space environment for commerce, science, exploration, and defense. In order to achieve these objectives, the United States needs to give greater attention to launch and mission operations, the collection of processes and procedures used to ready vehicles and spacecraft for launch and insertion into orbit. Launch operations make up a significant percentage of launch costs.

The United States already uses or has under development a variety of technologies that can make launch operations more reliable, efficient, and cost effective. However, as this technical memorandum explains, the United States has spent relatively little effort in applying them to operations. Just as important as cost saving technologies are appropriate management methods, or strategies, to put these technologies to work. In some cases, OTA has found, cost savings could be achieved by streamlining operations and reducing the burden of documentation and reporting requirements that have slowly expanded over the years.

This memorandum is part of a broader OTA assessment of space transportation requested by the House Committee on Science, Space, and Technology, and the Senate Committee on Commerce, Science, and Transportation. In July, OTA released a companion volume, *Launch Options for the Future: A Buyer's Guide,* which explores several possible options for space transportation systems.

In undertaking this technical memorandum OTA sought the contributions of a broad spectrum of knowledgeable individuals and organizations. Some provided information, others reviewed drafts. OTA gratefully acknowledges their contributions of time and intellectual effort. As with all OTA reports, the content of this technical memorandum is the sole responsibility of the Office of Technology Assessment and does not necessarily represent the views of our advisors or reviewers.

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Related OTA Reports

Civilian Space

- *Launch Options for the Future: a Buyer's Guide*. OTA-ISC-383, July 1988. GPO stock #052-003-01117-4; $5.00.
- *Commercial Newsgathering From Space*. OTA-TM-ISC-40, May 1987. GPO stock #052-003-01066-6; $3.00.
- *Space Stations and the Law: Selected Legal Issues*. OTA-BP-ISC-41, September 1986. GPO stock #052-003-01047-0; $3.75.
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Executive Summary

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Chapter 1

Executive Summary

INTRODUCTION

Achieving low-cost, reliable space transportation is one of the most important space policy challenges facing the United States today. The Nation's ability to assure timely access to space, to guarantee the general welfare of U.S. civilian space activities, and to compete effectively with other countries depends on meeting this challenge squarely and thoughtfully.

Ground and mission operations processes are highly complex and involve a wide variety of technologies. As support functions, they only become obvious to the public and to Congress when they fail to work properly. Because they constitute a significant percentage of launch costs, reducing the costs of these operations is crucial to lowering the overall costs of space transportation. Improved operations technology and management could also lead to greater flexibility and responsiveness to changing conditions in space activities. Yet these relatively mundane processes and procedures seldom receive close scrutiny from the Congress, or attention from the policy community.

This technical memorandum is intended to help Congress understand the launch process and how the use of advanced technologies and management techniques could reduce the costs of launching payloads. It does not discuss the management of payloads or crews for passenger-carrying vehicles.

The memorandum is part of an assessment of advanced launch technologies, which was requested by the House Committee on Science, Space, and Technology, and the Senate Committee on Commerce, Science, and Transportation. It derives in part from a workshop held at OTA on September 10, 1987, which met to discuss issues of launch operations technology and man-

Box 1-A.—Launch Operations Processes

Launch operations includes the procedures necessary for launching payloads to orbit. It does not include the management of payload or crew (for piloted vehicles) on orbit, which are generally considered mission operations. Launch operations can be divided into the following overlapping steps:

- *Processing and integration of vehicle:* includes the assembly and testing of the launch vehicle, as well as the integration of electrical, mechanical, and fluid systems. For reusable, or partially reusable vehicles, this step also includes testing of refurbished components to assure that their characteristics remain within design specifications.
- *Processing and integration of payloads:* comprises the assembly, testing, and mechanical and electrical integration of payloads with the launch vehicle. Payloads must also be tested with the vehicle's mechanical and electrical systems to assure they will not interfere with proper operation of the launch vehicle.
- *Launch management and control:* includes the preparation and testing of the launch pad, the control center, and all of the other facilities critical for launch, as well as the actual launch countdown. During countdown, each critical subsystem must be continually monitored.
- *Post launch responsibilities:* includes the retrieval, return, and refurbishment of all reusable vehicle components, and the cleanup and post-launch refurbishment of the launch pad. The launch of reusable, or partially reusable, vehicles introduces an extra layer of complexity to the launch process and involves additional facilities and personnel.
- *Logistics:* encompasses the provision of spares, and replacement parts, as well as the scheduling of tasks, personnel, and equipment, which must be coordinated across the entire launch process.

agement, and from OTA staff research. OTA staff visited Air Force and National Aeronautics and Space Administration (NASA) facilities[1] and gathered additional information from a literature review and personal interviews with individuals from the major aerospace firms.

PRINCIPAL FINDINGS

Finding 1: Because launch and mission operations constitute a sizable fraction of the cost of launching payloads to orbit, developing new launch vehicles will not, in itself, result in significant reductions of launch costs. If the United States wishes to reduce launch costs, system designers and policymakers must give greater attention to operations.

Because launch and mission operations are responsible for up to 45 percent of the cost of each launch, lowering these costs is crucial to reducing the overall cost of space missions. Prompted by the needs of the spacecraft community, launch system designers have traditionally focused greater attention on achieving high performance than on operational simplicity or low cost. Recently, plans for a permanently inhabited space station, more extensive Department of Defense (DoD) space activities, and problems with existing U.S. launch systems have suggested the desirability of attaining routine, low-cost launch operations. NASA and DoD have funded several studies aimed at identifying technologies and management practices capable of reducing the costs of launch services.[2] The results show that a variety of technologies, either new or in use in other industries, could help to reduce operations costs. They also indicate that important reductions of launch costs are unlikely unless launch operations engineers and facilities managers have a greater role in the design of future launch systems. The development process should encourage a thorough and frequent interchange of information and ideas among representatives from operations, logistics, design, and manufacturing. It should also contain sufficient incentives for reducing costs.

Finding 2: Technologies capable of reducing the recurring costs of ground and mission operations exist today or are under development in a variety of fields.

These include technologies for:

- built-in test equipment;
- management information systems;
- automated test and inspection;
- advanced thermal protection systems;
- fault-tolerant computers;
- adaptive guidance, navigation, and flight control;
- automated handling of launch vehicles and payloads;
- computer-aided software development; and
- expert computer systems.

Some of these technologies could be incorporated into the design of the launch vehicle. For example, built-in test equipment and software could be used to detect faults in vehicle subsystems, reducing ground operations labor and cost. Other technologies might find application in the launch and mission operations facilities. For example, management information systems could sharply reduce the amount of human effort in making, distributing, and handling paper schedules and information. Such systems could also reduce the number of errors experienced, and speed up sign-off procedures.

The amount of money such new technologies could save, either from building new launch systems, or from enhancing existing systems, depends strongly on three factors: 1) the demand for launch services, 2) the non-recurring costs of technology development and facilities, and 3) savings achieved in operations. Unless launch demand for the late 1990s increases sharply over current estimates, adopting new technologies could actually increase the total (life-cycle) cost of space transportation.

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[1] OTA site visits included: Air Force Space Division, Los Angeles; Cape Canaveral Air Force Station; Edwards Air Force Base; Johnson Space Center; Kennedy Space Center; Langley Research Center; Marshall Space Flight Center; Vandenberg Air Force Base.

[2] The results of these studies are summarized in the report of the Space Transportation Architecture Study: U.S. Government, *National Space Transportation and Support Study 1995-2010*, Summary Report of the Joint Steering Group, Department of Defense and National Aeronautics and Space Administration, May 1986.

Finding 3: Dramatic reductions in the costs of launch operations (factors of 5 to 10) could be achieved only under highly limited conditions.

Most experts OTA consulted thought that reductions in operations costs by five- or ten-fold, as suggested by the Space Transportation Architecture Study and the Advanced Launch System (ALS) program,[3] were unobtainable in practice even with proposed new technology and new facilities. They pointed out that although the large capacity vehicles contemplated for an ALS might save costs by carrying more weight, they would not be efficient for smaller payloads. In addition, new ground facilities (e.g., launch complexes, fabrication and assembly buildings) typically require investments of several hundred million or even billions of dollars. Such investments seldom look attractive in the short run—the most relevant time period in a stringent budget environment—and are therefore seldom adequately funded. Finally, dramatic reductions in cost would require significant changes in the institutional mechanisms of launch operations, which would be very difficult to achieve without considerable institutional upheaval.

Such reductions would require high launch demand, a new generation of launch vehicles and ground facilities designed to accommodate rapid turn around, and payloads of uniform design and orbital characteristics. In theory, it would be possible to create new advanced-technology launch systems, such as those proposed for the ALS program. These launch systems would be most beneficial for launching many payloads with similar technical and orbital characteristics, such as components of a space-based missile defense system, or perhaps fuel to send humans to and from Mars. Absent a decision to deploy SDI, or to increase sharply spending on civilian payloads, the number and diversity of payloads NASA and DoD now plan to launch through the late 1990s do not meet the conditions necessary for dramatic cost reductions.

Thus, under these conditions, the *discounted life-cycle cost*—the total of recurring and nonrecurring costs, appropriately discounted—of launching known or currently projected payloads probably can be reduced only marginally by developing completely new launch systems. In addition, because a revolutionary launch design such as envisioned for ALS would involve new design approaches and some new technologies,[4] the technological and economic risks would be higher than for an evolutionary approach.

Finding 4: If the Federal Government wishes to invest in new operations technologies, it should have clear long-term goals and a well-defined plan for developing and incorporating new technologies in space transportation operations. Such a plan must be buttressed by data from new and more reliable cost models.

NASA and the Air Force are funding research on new technologies for launch systems. NASA's Civil Space Technology Initiative (CSTI) is pursuing research on a number of technologies, including autonomous systems and robotics, that could improve some launch procedures and might even lead to cost savings. NASA and the Air Force are collaborating on research in the Advanced Launch System's Focused Technology Program, which may contribute to reducing the costs of launch and mission operations. Yet these research programs devote only a small percentage of their budget to space transportation operations. In addition, no well-organized or well-funded plan exists to *apply* the technologies developed in these programs to launch operations procedures, or to coordinate research being carried out through the existing technology R&D programs.

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[3] See especially U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988), for an extensive discussion of launch system costs and capabilities.

[4] U.S. Government, *National Space Transportation and Support Study 1995-2010*, Summary Report of the Joint Steering Group, Department of Defense and National Aeronautics and Space Administration, May 1986.

In fiscal year 1989, NASA plans to start an Advanced Operations Effectiveness Initiative, which would develop and carry out a plan for inserting the results of technology R&D into launch and mission operations. However, NASA is allocating only $5 million to this initiative in the 1989 budget, an amount that will have a very small effect on reducing launch and mission operations costs.

To complicate matters, the current restrictive budgetary environment makes it difficult to spend money *now* on research and facilities that *might* save money later. To respond to this suite of technical, institutional, and budgetary challenges, the United States needs a coherent long-term plan for developing and incorporating new operations technologies into existing and future launch systems. A technology development plan should include work in all development phases:

- broad technology exploration (basic research),
- focused research leading to a demonstration, and
- implementation to support specific applications.

Such a plan should be part of a more comprehensive National Strategic Launch Technology Plan that would develop and insert new technologies into U.S. launch systems.

Instituting a long-term research, development, and technology application plan will be extremely difficult for three reasons. First, policymakers in Congress and the Administration have been unable to agree on overall long-term goals for the publicly funded U.S. space program. Operations procedures optimized for our current level of space activities would differ substantially from those designed to deploy space-based defenses or mount a mission carrying humans to Mars.

Second, current ground and mission operations are partially controlled or influenced by the technologies and management requirements from a dozen or so different research centers, hundreds of technical projects, and thousands of individuals in NASA, DoD, and the aerospace industry. The Administration's latest space policy statement directs NASA and DoD to cooperate in pursuing "new launch and launch support concepts aimed at improving cost-effectiveness, responsiveness, capability, reliability, availability, maintainability, and flexibility."[5] This directive could provide the impulse for developing a national research and development plan. However, the institutional structure and will to focus the efforts of these interested parties on the common purpose of reducing operations costs does not presently exist. Until Congress and the Administration reach agreement on specific national space policy goals, developing an effective, detailed, multi-year plan for developing and incorporating new technologies into space transportation operations will be extremely difficult. Encouraging NASA and DoD to reduce operations costs substantially may require making major institutional changes to these agencies, or developing a new agency for operations.

Finally, the lack of objective, verifiable cost estimation models makes it difficult to determine which technologies are worth pursuing or which should be discarded. Credible, objective operations cost methods—similar to those of the airline and other commercial industries—should be developed, which would allow the Government to estimate the total cost of incorporating a new technology or management practice and the savings it could generate. Current models have proven inadequate, in part because data on previous launch operations experience have neither been collected in an organized way nor properly maintained. Without adequate historical data to use as a benchmark, cost estimation involves too much guesswork. Congress may wish to direct NASA and DoD, or some independent agency, to collect the necessary historical data and to develop better cost estimating methods for space transportation systems.

Finding 5: Although making evolutionary improvements to *existing launch systems* may prove difficult and expensive, such improvements could reduce the cost of existing launch and mission operations.

Because launch vehicles and their ground support facilities are highly integrated and interdependent, it is difficult and expensive to incorporate new cost or time saving technologies. Nevertheless, experts consulted by OTA agreed that it would be possible to reduce operations costs by improving vehicle subsystems such as onboard avionics, and many ground-based support activities such as payload handling and fuel loading, through redesign, automation, and standardization. Technologies pursued for new launch systems may have application to existing systems and vice-versa.

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[5] "Presidential Directive on National Space Policy," White House Office of the Press Secretary, Fact Sheet, Feb. 11, 1988.

Finding 6: It will be difficult to improve the way the United States manages its launch operations without making significant changes to the institutions currently responsible for those operations.

Current U.S. space management practices result from a launch operations philosophy that emphasizes long-lived, expensive payloads, high-performance launchers, very high reliability, and low launch rates. The Soviet Union, on the other hand—both by choice and as a result of its limited technology base—has in the past relied on relatively inexpensive short-lived satellites, reasonably reliable vehicles, and very high launch rates. As a result, the Soviet launch infrastructure is more "resilient" than its U.S. counterpart, although not necessarily more effective at accomplishing national goals.

The United States is now in the difficult position of attempting to retain its high-technology, high-performance approach to payloads and vehicles while attaining Soviet-style routine, lower cost access to space. This goal is probably unattainable unless the U.S. Government substantially alters the way it conducts space transportation operations. Such an alteration would require significant changes to the institutional structure and culture of NASA and DoD.

Congress could direct the Air Force and NASA to:

- turn launch operations for all new launch systems over to the private sector;
- establish operations divisions fully independent of launcher development, including development of a Shuttle or an ALS; or
- purchase launch services, rather than vehicles, from the private sector for existing ELV launch systems.

One way to manage the institutional challenge is to maintain separate institutions for launch vehicle development and operations by turning over operation of new launch systems to the private sector. Under such an arrangement, the launch company would assume control of launch operations after the systems were developed and would provide launch services to the Government on a contractual basis. In order to further reductions of cost, the company would also be encouraged to market its services to other payload customers, either from the United States or abroad. The European Space Agency (ESA) and Arianespace have demonstrated that such an arrangement can be highly effective. ESA funded development of the Ariane launch system under the management of the French space agency, CNES. Arianespace, S.A., a French corporation, which manages the Ariane operation and markets the Ariane launcher worldwide, set requirements for a successful commercial venture.

Although the European model may not be fully applicable to U.S. conditions, Congress must find ways to give space transportation operations extra visibility and "clout" so they will not be considered a costly afterthought. Congress could direct NASA and the Air Force to establish operations divisions fully independent of each agency's launch development organization, with the charge of operating launchers on the basis of increased efficiency and reduced costs. This would require considerable congressional oversight to assure that the agencies carried out the will of Congress.

NASA and DoD could also reduce operations costs by purchasing all expendable launch services, rather than launch vehicles, from the private sector for existing systems. Recent Administration policy directs the civilian agencies, including NASA, to purchase expendable launch services from private companies. However, the policy allows considerable latitude for DoD to continue its current practice of involving Air Force personnel deeply in the launch process.

Finding 7: In addition to new technologies, adopting new management practices and design philosophies could increase the efficiency and reduce the cost of ground operations.

Management strategy may often be more important than new technology for achieving low cost launches. Cost-reducing strategies include:

- reduce documentation and oversight,
- create better incentives for lowering costs,
- provide adequate spares to reduce cannibalization of parts,
- develop and use computerized management information systems, and
- use an improved integrate/transfer/launch philosophy.

Some management strategies could be enhanced through the appropriate use of technology. For example, OTA workshop participants pointed out that operations costs will never fall significantly unless ways are found to reduce the time consumed by human documentation and oversight. In many cases, automated procedures would reduce the need for certain documentation, and certainly shrink the necessary manpower to maintain it. However, reducing the amount of oversight significantly will be much more difficult. Since the Titan and Shuttle losses of 1985 and 1986, the number of Government personnel responsible for contractor oversight has increased.

Also needed are incentives to encourage lower operations costs. The current institutional management structure tends to penalize launch failure, but is poorly structured to reward the lowering of launch costs or increases in launch rate. However, the Strategic Defense Initiative Organization found in a recent project[6] that it was able to cut overall project costs in half by incorporating simple, common-sense management techniques such as reducing Government oversight, delegating authority to those closest to the technical problem, maintaining short schedules, and paying employees bonuses for meeting deadlines. Although the team was able to achieve some of its operations cost savings as a result of a concentrated, narrow effort that would be difficult to maintain for routine launches, the project nevertheless demonstrated that a management philosophy that includes incentives for launch managers and technicians can play a significant role in reducing the cost of launch operations.

Vehicle design can also play a crucial part in the ability to reduce launch and mission operations costs. The accessibility of critical parts, the weight and size of components, and the ability to change out modules quickly all affect the speed and effectiveness of operations. Several design principles are particularly important. One should:

- engage all major segments of launch team in launch system design process;
- design for simplicity of operation as well as performance; and
- design for accessibility, modularity, and simplicity of operation.

For example, considering all elements of the launch system, including the operations infrastructure and operations management, as a collection of highly interactive parts will allow system designers to anticipate potential operations and maintenance problems and provide for them before the system is built. As was discovered with the Space Shuttle main engines, certain subsystems may pose unexpected maintenance problems. All major subsystems should be designed to be readily accessible, and, as much as possible within weight and size constraints, should also be of modular design in order to reduce maintenance and integration costs.

Many concepts for improved launch operations tend to shift costs from operations to other stages in the launch services process, such as payload processing. For example, requiring payloads to provide their own internal power, rather than relying on a source in the launcher, may reduce ground operations costs, but could also increase the cost of preparing payloads. In altering the structure of space transportation operations, such changes in procedure or technology should not merely send problems elsewhere.

Finding 8: Unless the Government can stimulate the innovative capacity of the private sector, private sector contributions to reducing the costs of space transportation operations will continue to be quite limited.

Almost all of the recent effort in improving launch operations has been instigated by NASA and the Air Force in connection with the Space

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[6] The Delta 180 experiment. See ch. 2, *Issues*, for a discussion.

Transportation Architecture[7] and the Advanced Launch System studies.[8] Private sector initiatives, such as competitive bidding for components, and introducing some new technologies, show what can be done in a modest way to reduce costs. However, these efforts are still relatively limited and reflect the tenuous nature of the U.S. commercial launch industry.

The Government could use the talents of the private sector most effectively, and in the process encourage a more competitive industry, by purchasing the services of expendable launchers rather than vehicle systems, and by offering strong incentives for decreasing costs. Although it is theoretically possible for the Government to purchase services for piloted launchers, such as the Space Shuttle, private industry is unlikely to offer such services in the near future because the technologies of reusable vehicles are still immature and the costs of change are great.

Congress could also enhance the development of new operations technologies and assist private sector competitiveness by funding an "operations test center" composed of a mock launch pad and facilities. Such a center should be specifically designed to enable tests of new technologies for incorporation into existing and new launch systems. The ability to try out new operations technologies on a working launch pad is limited. A center would give the private sector the opportunity to try out new operations technologies free from the demands of routine operations. Such a center could be a government-owned, contractor-operated facility. Alternatively it could be partially funded by the private sector, and operated by a consortium of Government agencies, private sector companies, and universities.

Finding 9: For certain aspects of launch operations, the broad operational experience of the airlines and the methods they employ to maintain efficiency may provide a useful model for space operations.

Although airline operations face different technical and managerial constraints than space launch operations, certain airline methods used in logistics, maintenance, task scheduling, and other ground operations categories could make launch operations more efficient and cost-effective.

The following airline practices could be of particular interest for space transportation operations:

- involve operations personnel in design changes;
- develop detailed operations cost estimation models;
- stand down to trace and repair failures only when the evidence points to a generic failure of consequence;
- design for fault tolerance;
- design for maintainability;
- encourage competitive pricing;
- maintain strong training programs; and
- use automatic built-in checkout of subsystems between flights.

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[7] U.S. Government, *National Space Transportation and Support Study 1995-2010*, Summary Report of the Joint Steering Group, Department of Defense and National Aeronautics and Space Administration, May 1986.

[8] The results of seven contractor reports for phase I of these studies have not yet been released. ALS phase II studies are scheduled to begin in August 1988.

Chapter 2

Major Issues in Launch and Mission Operations

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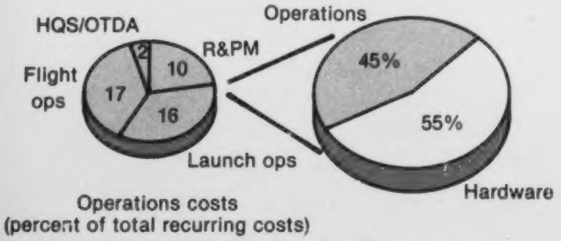
Chapter 2

Major Issues in Launch and Mission Operations

INTRODUCTION

Launch and mission operations constitute a significant fraction of the cost of launching payloads to orbit. For example, prior to the loss of Challenger, Shuttle operations costs, including mission operations, accounted for about 46 percent of the cost of a flight. Of that, ground operations totaled at least 24 percent (fig. 2-1). Projected lifecycle costs of the Shuttle suggest that some 86 percent of the total can be attributed to the recurring costs of launch and mission operations.[1] Because of recently mandated safety-related modifications, recurring costs are likely to be higher when the Shuttle flights resume. For today's expendable launch vehicles (ELVs), operations costs are generally a smaller percentage of the total, in large part because these vehicles do not contain reusable components and do not carry humans. However, they are still significant. For example, in the Titan series, launch operations costs can reach about 20 percent of total costs per flight (fig. 2-2).

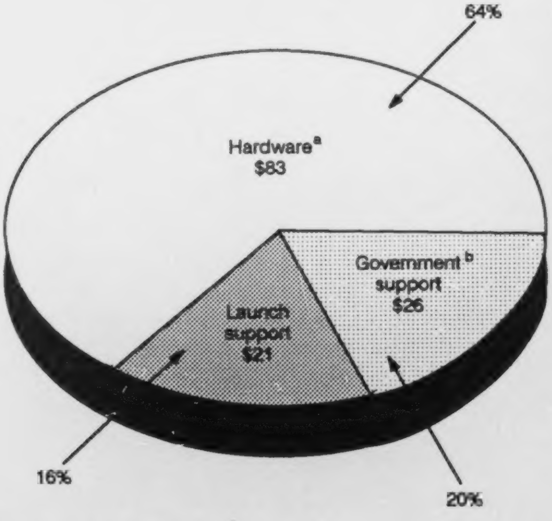
Figure 2-1.—Shuttle Recurring Cost (percent per flight)



SOURCE: National Aeronautics and Space Administration.

Attempts to reduce operations costs must cope with the complexity of launch and mission operations, and the relative lack of policy attention they have received over the years. Workshop participants and others who contributed to this study[2] identified the following primary issues that should be addressed in developing a sound Federal policy toward reducing costs and increasing efficiency of launch and mission operations.

Figure 2-2.—Titan IV Estimated Cost per Flight (in millions)



[a]Hardware costs based on annual buy rate of 6/yr.
[b]Government costs include propellant, range support, incentives, Aerospace Corporation support, etc.

SOURCE: Aerospace Corp.

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[1] National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technologies Study," Kennedy Space Center, NAS10-11344, May 4, 1987.

[2] The many interim reports related to the Space Transportation Architecture Study and the Advanced Launch System effort provided much of the initial information for OTA's effort. In addition, the study team interviewed officials from the Air Force, NASA, and private industry.

MAJOR ISSUES

ISSUE A: Can New Technologies and Management Strategies Reduce Operations Costs?

Existing Systems

Evolutionary improvements to existing launch systems appear to provide opportunities for making modest, but meaningful, reductions in ground and mission operations costs. Reducing operations costs for existing launch systems generally means reducing the size of operations staffs and shortening the time it takes to prepare and launch a vehicle. Vehicle subsystems, such as avionics, and many ground-based support facilities can be improved through redesign, automation, and standardization.[3]

It is extremely costly to shorten vehicle turnaround and processing substantially by making incremental upgrades of the vehicle, because vehicle subsystems are highly integrated and interdependent. As a result, altering one subsystem often requires changing others. For example, even small alterations of the orbiter outer structure may require significant changes of parts of the thermal protection system. Box 2-A presents a list of changes that could be required in other systems if the design of the Shuttle main engines were materially altered. Such changes would involve multiple NASA centers and contractors, and require considerable coordination.

Commercial launch companies are investing in performance improvements and exploring ways to reduce launch operations costs. For example, General Dynamics has developed a new avionics package for the Atlas-Centaur that reduces the weight of the avionics package and increases its reliability. It also includes self-testing procedures that will reduce operations costs slightly. Other launch companies are exploring similar ways of reducing costs of the launcher and launch operations.

Because changes in the design of vehicle subsystems often have a direct effect on ground operations or mission operations procedures, it is important for design engineers to work closely with operations personnel to establish the best way to proceed in making changes appropriate to operations and maintenance processes. Whether particular changes will result in net reductions in life-cycle costs will depend on a variety of economic, technical, and managerial factors. Chapter 4 discusses these factors for several specific cases.

Box 2-A.—Required Changes to Other Shuttle Subsystems If Shuttle Main Engines Are Altered Significantly

- *Main Engine Controller (computer) hardware and software.*
- *Engine Interface Unit Hardware*—device that couples the main engine controller computer to the General Purpose Computer network.
- *Flight Software Applications* executing in the General Purpose Computer Complex.
- *The Pulse Code Modulation Master Unit data access programs and telemetry formats*—device that receives data from the main engine for telemetry to Earth.
- *Various Ground Checkout hardware and software at KSC*—especially the Launch Processing System applications software.
- *Mission Control Center software*—used for monitoring of engine performance during launch.
- *Main Engine Environment Models*—used in the following simulation and test facilities:
  —Software Production Facility
  —Shuttle Mission Simulator
  —Shuttle Avionics Integration Facility
  —Various flight design engineering simulators

Although new technology or design changes may lead to reduced costs, management changes may be more important. For example, a recent Strategic Defense Initiative Organization experiment called the Delta 180 Project used new management techniques to achieve reduced project costs. Project managers found that decreasing the burden of oversight and review, and delegating authority to those closest to the technical problems, resulted in meeting a tight launch schedule and reducing overall costs.[4] Maintaining a short schedule (fig. 2-3) reduced overhead costs of the entire project by about 50 percent. In part this was achieved by giving contractors cash incentives to achieve the demanding project schedule. Company employees shared in bonuses paid to the company for meeting deadlines, which gave them strong incentives to increase productivity. Table 2-1 lists the major factors that led to lower costs and shorter project schedules for the Delta 180 project. Although the team was able to achieve some of its cost savings as a result of a focused, narrow effort, which would be difficult to maintain for routine launches, the project nevertheless demonstrated that management philosophy can play a significant role in reducing the costs of launch operations.

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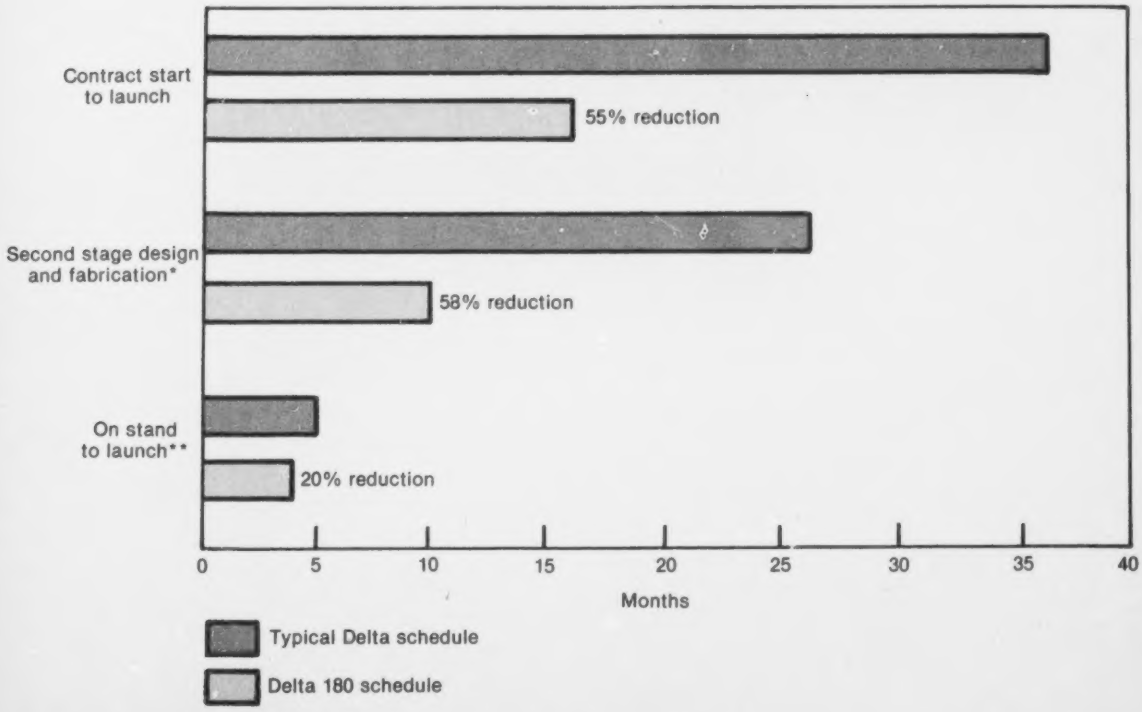
[3] National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technology Study," KSC Report NAS10-11344 Boeing Aerospace Operations Co., May 4, 1987.

[4] Department of Defense Strategic Defense Initiative Office/Kinetic Energy Office, "Delta 180 Final Report," vol. 5, March 1987.

Today launch system planners are focusing directly on reducing the labor and attendant costs of launch operations. Historically, the chief means of reducing operations costs, relative to achieved lift capacity, is to increase vehicle performance. Over the years, NASA, the Air Force, and the launch vehicle manufacturers have made incremental improvements to launch system performance and reliability[5] that have also led to operations cost savings. For example, in its early flights in the 1960s, the Delta was able to launch only 100 lbs. to geosynchronous transfer orbit (GTO). Today, the Delta can launch over 2,800 lbs. to GTO. Launch operations costs[6] are now about 10

Figure 2-3.—Delta 180 Project Schedule Reductions



*Represents design and fabrication of the PAS—essentially a new third stage.
**Includes the PAS which doubles requirements of a normal Delta launch.

SOURCE: National Aeronautics and Space Administration.

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[5] The Space Shuttle presents a counter example. Because of the desire to improve the safety of Shuttle crews and payloads, the payload capacity of the Shuttle has actually decreased over the years. Originally designed to carry about 65,000 lbs. to low Earth orbit (at 160 nautical miles), the Shuttle's payload capacity is now only about 48,000 lbs.

[6] These costs include only contractor personnel and other recurring costs directly attributed to the launch. They do not include maintenance and other general costs associated with the launch pad.

Table 2-1.—Cost Reduction Factors for the Delta 180 Project

- Given program autonomy—minimum program management and reporting
- Short statements of work—2 pages
- Organized in terms of working groups responsible for specific tasks—given autonomy to solve problems within working groups
- Within working groups, contractors worked as an integrated team from the beginning—close contact among all team members, open discussion

SOURCE: Department of Defense Strategic Defense Initiative Office/Kinetic Energy Office, "Delta 180 Final Report," vol. 5, March 1987.

percent of the total costs per flight. Performance improvements to the Delta[7] (designated a Delta II) should increase its lift capacity to 4,000 lbs. to GTO, but are not expected to alter significantly the complexity or the cost of ground operations, though the cost of the vehicle has certainly increased.[8] Hence, should the per flight costs directly attributable to operations remain constant, operations costs of the Delta II per pound[9] could decrease by about 40 percent compared to the current Delta launcher.[10] [11] Historically it has taken about 150 resident McDonnell Douglas personnel at Cape Canaveral to perform the launch vehicle processing activity at a 6-launch-per-year rate. This includes all administrative functions, ground support equipment operation and sustaining, procedure preparations, payload integration and launch vehicle processing through launch.

New Launch Systems

Several recent studies[12] have suggested that starting fresh and designing to cost rather than for performance would lead to significant reductions in the costs of launch operations. These studies identified several approaches to system design. The OTA workshop generated its own list of design goals (table 2-2). The discussion in chapter 4 elaborates on these goals, and lists a number of technologies that would serve them.

NASA and the Air Force are working on a variety of new launch system designs. In particular, they are collaborating on a major study of an Advanced Launch System (ALS), whose goals are to increase the payload capacity per launch by a factor of 3 or 4 and to reduce the cost per pound of launching payloads to space by an order of magnitude.[13] Although a "clean sheet of paper" approach to launch system design offers potential benefits in reducing life-cycle costs, it also increases the technical and cost risk of launch system manufacturing and operations. In addition, the non-recurring investment in new facilities, and research and development, will offset part of the savings in recurring costs anticipated from such changes.[14] Thus it is necessary to address the entire set of launch procedures, including aircraft, trains, barges, and other auxiliary facilities, which function as a single integrated system.

ISSUE B: Is the United States Devoting Adequate Attention To Reducing the Costs of Space Transportation Operations?

Both NASA and the Air Force are funding research on new technologies for launch systems. Yet only a small percentage of this research is devoted to development of technologies for space transportation operations and only part of this is directed toward improving existing operations.

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[7] McDonnell Douglas is making these improvements in connection with the Air Force MLV program. The first Delta II launch is expected in 1989.

[8] Lyle J. Holloway, McDonnell Douglas Astronautics Co., 1987.

[9] This example illustrates one kind of savings possible as vehicles are improved. However, for many purposes, figuring costs of launching payloads on a per pound basis may not be appropriate. The life-cycle cost of a launch system for a given collection of payloads over the years is often a more appropriate measure. See U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

[10] These performance improvements will be accomplished by improved solid rocket booster engines and an improved main engine.

[11] Concurrently, the Delta launch crew efficiency has also improved, resulting in a higher percentage of launch successes, and the potential for a higher launch rate (box 2-B). Delta has improved its launch success rate over the years from 93 percent (170 out of 182 launches) in the 1960s to nearly 98 percent in recent years (one failure in 48 launches since 1977).

[12] U.S. Government, *National Space Transportation and Support Study 1995-2010*, Summary Report of the Joint Steering Group, Department of Defense and National Aeronautics and Space Administration, May 1986; Advance Launch System Phase I Study briefings, 1987, 1988.

[13] See U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988), ch. 5.

[14] Ibid., ch. 7.

Box 2-B.—The Delta Experience

The following illustrates one company's experience in providing launch services to the Government.

- *Minimal oversight*. Part of the key to lowering launch operations costs is to keep the number of Government personnel devoted to overseeing contractor preparations as small as possible. Responsibility for management of the Delta program has recently shifted to DoD. When under the management of NASA, McDonnell Douglas' main customer for Delta launches was the NASA Goddard Space Flight Center (GSFC), whose primary mission is the preparation and launch of NASA's scientific payloads. GSFC employed 15 to 20 engineers to oversee the Delta launch operations. The GSFC team was kept deliberately small, to avoid the temptation to over-manage McDonnell Douglas' launch preparations. McDonnell Douglas attempted to discuss launch problems and resolve them with GSFC immediately. GSFC personnel worked with the contractor's internal documentation, and if a Government or military specification or procedure showed greater risk in cost than it was likely to return in increased reliability it was discarded or tailored. Documentation requirements were kept to a minimum.
- *Self-sufficiency*. McDonnell Douglas has minimized the number of associate contractors or subcontactors with their own independent documentation procedures and systems necessary to work on the vehicle or facility. In addition, the Delta team prepares the vehicle on the basis of a single Launch Preparation Document, which includes inputs from all departments. It gives all requirements for assembly and test of the vehicle, traceability and accountability of all flight and non-flight hardware, and of all test and operational requirements. Daily meetings near launch time with all the technicians, inspectors, test engineers, managers, and the customer for the launch, enables significant problems to surface. This results in a single, informed team with a common objective.
- *Mindset toward economy*. Although the Delta has always been operated on a budget typical of small scientific or commercial payloads, in the late 1970s McDonnell Douglas began to explore new ways to economize on the Delta when it became apparent that Government use of all ELVs was to be phased out after the Space Shuttle became operational. McDonnell Douglas funded (with RCA) the development of upgraded Castor IV strap-on solid rockets, which increased Delta payload capacity 50 percent, and also found ways to economize on launch operations procedures. Although each individual step has been small, over time, such steps have made the entire set of procedures more cost effective.

SOURCE: McDonnell Douglas Astronautics Corporation.

Table 2-2.—Approaches to Low-Cost Launch Design

- Include all segments of the launch team (including managers) in the design of a new launch system
- Reduce launch system complexity
- Increase maintainability
  - —Increase subsystem accessibility
  - —Design for modularity
  - —Include autonomous, high-reliability flight control and guidance systems
  - —Build in testing procedures, for mechanical and fluid systems, as well as for electronic systems
- Make payloads independent of launcher, with standardized interfaces

SOURCE: Office of Technology Assessment, 1988.

Through its Office of Aeronautics and Space Technology, NASA has funded a Civil Space Technology Initiative (CSTI), which is pursuing research on a number of technologies, including autonomous systems and robotics, that could improve some launch procedures and might even lead to cost savings (table 2-3).

As part of the CSTI, all the NASA centers are involved to some extent in the Systems Autonomy Technology Program, which has been designed to develop and demonstrate the feasibility of using "intelligent autonomous systems" in the U.S. civilian space program, and to enhance NASA's in-house capabilities in designing and applying autonomous systems. Some of these systems, if successful, will have direct applications for launch and mission operations. For example, the Systems Autonomy Technology Program is developing an online expert system to assist flight controllers in monitoring and managing Space Shuttle communications. It is also developing the hardware and software for autonomous diagnostics and control for the KSC Launch Processing

System. Both systems would increase the reliability and capability of mission and launch operations and could eventually lead to reductions in the number of personnel necessary for these tasks.

The CSTI is designed to demonstrate the feasibility of selected technologies. However, without a clear and focused plan for choosing which technologies are needed for launch and mission operations, and inserting them into existing procedures, they may not be applied effectively. The NASA Office of Space Flight is planning an Advanced Operations Effectiveness Initiative, to begin in fiscal year 1989, that would provide plans for inserting new technology into launch and mission operations. Though funded at only $5 million per year, this initiative should play an important role in improving operations procedures, because it can verify, validate, and demonstrate technologies developed under the CSTI. In the long run, it could also lead to lower operations costs. Congress could consider funding this program at a higher level.

Through the Focused Technology Program, funded within the Advanced Launch System program, NASA and the Air Force are working together on research crucial to reducing operations costs. Some of these technologies may also contribute to improving the efficiencies of existing systems (table 2-4).

The National Aeronautics and Space Act of 1958 gave NASA the responsibility of "the preservation of the role of the United States as a leader in aeronautical and space science and technology."[15] Its role as a research and development (R&D) organization is firmly imbedded in its institutional culture. The Air Force is mission oriented; its launch systems organization is therefore organized to respond to the special transportation needs of the DoD payload community. Both organizations have developed different institutional cultures applying different operational approaches, which occasionally lead to costly friction in programs of mutual interest. For example, in the area of launch vehicle R&D development, the two organizations continue to compete for funding and for program lead. Yet, especially in this era of budget stringency, the Air Force and NASA must work together more effectively on research to improve existing systems and develop the next-generation launch systems.

Table 2-3.—Civil Space Technology Initiative Funding (in millions)

Program area	FY 88	FY 89 (requested)
*Automation and robotics	$25.1	$25.9
Propulsion	23.8	46.7
Vehicle (aeroassist flight experiment)	15.0	28.0
*information technology	16.5	17.1
Large structures and control	22.0	25.1
Power	12.8	14.0
Total	$115.2	$156.8

*Technologies of importance to launch and mission operations.

SOURCE: National Aeronautics and Space Administration.

ISSUE C: What Factors Impede the Introduction of New Technologies and Management Strategies in Launch and Mission Operations?

Existing launch and mission operations are extremely complicated, and have unique requirements for technology, facilities, and management. For example, operations procedures may necessitate airplane runways; test facilities for a wide variety of equipment; massive, environmentally controlled buildings for launcher assembly and checkout; and fixed and mobile launch pads. Logistics, including the provisions of parts and supplies, contributes its own complexities. Each facility adds additional complexity and distinctive management requirements. In addition, the Government is both financially and institutionally invested in existing operations procedures. The following factors make it difficult to reduce operations costs significantly for existing launch systems:

Investment in Existing Infrastructure.—The United States has already invested billions of dollars in facilities at Kennedy Space Center (KSC), Johnson Space Center (JSC), Cape Canaveral, and Vandenberg.

From a near-term budget perspective, it is easier to justify refurbishing old facilities than to build totally new ones because the short term costs are often lower. However, existing facilities that were built for earlier launch programs require continued modernization and repair, and the resulting inefficiencies become part of the work flow

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[15] National Aeronautics and Space Act, Sec. 102(5), 24 U.S.C. 2451.

Table 2-4.—Advanced Launch System Focused Technology Program (in millions of 1988 dollars)

	Year				
	1987/88	1989	1990	1991	1992
Propulsion:					
Engine definition/demonstration	$ 12.00	$ 6.00	$ 16.50	$ 30.10	$ 31.40
LOX/LH2 engine	17.60	26.80	45.60	18.20	9.60
LOX/LHc engine	32.90	16.30	32.90	28.60	11.50
Propulsion subsystems	0.50	1.40	4.50	5.60	4.00
Solid rocket booster	7.00	12.00	15.00	15.50	17.50
Propulsion facilities	24.00	34.00	20.00	7.00	2.00
Total	94.00	96.50	134.50	105.00	76.00
Avionics/Software:					
*Adaptive guidance, navigation and control	6.10	6.40	7.00	4.00	5.00
*Multi-path redundant avionics	10.30	0.00	0.00	0.00	0.00
*Expert systems	3.50	0.00	0.00	0.00	0.00
*Electromechanical actuators	6.50	0.00	0.00	0.00	0.00
Flight simulation lab	2.00	2.50	3.00	3.00	3.00
Total	28.40	8.90	10.00	7.00	8.00
Structures/Materials:					
Cryogenic tank(s)	14.00	15.00	15.00	19.00	12.00
Booster	3.00	6.00	6.00	8.00	11.00
NDE for SRB	1.00	2.00	4.00	4.00	2.00
Structural certification	8.00	5.70	10.00	3.00	1.00
Total	26.00	28.70	35.00	34.00	26.00
Aerothermodynamics/Flight mechanics:					
*Precision recovery	2.50	4.00	5.00	5.00	2.00
Multi-body ascent CFD	0.50	0.00	0.00	0.00	0.00
Aero data base	0.50	0.00	0.00	0.00	0.00
Base heating codes	0.50	0.00	0.00	0.00	0.00
Total	4.00	4.00	5.00	5.00	2.00
Ground and flight operations/Manufacturing:					
*Ground operations	14.10	7.00	13.00	12.00	7.00
*Health monitoring demo	4.00	4.63	5.16	4.63	3.58
*ManTech	4.50	5.20	7.22	5.70	4.03
Total	22.60	16.83	25.38	22.33	14.61
Grand total	$175.00	$154.93	$209.88	$173.33	$126.61

*Technologies of importance in launch and mission operations.

SOURCE: U.S. Air Force.

and extend throughout the life of the program.[16] For example, because the Vehicle Assembly Building, used for attaching the Shuttle orbiter to the external tank and solid rocket boosters, was originally built for the Saturn 5 program, it does not have the optimum size and shape for the Shuttle, which leads to longer and more complicated vehicle assembly. Thus, the long-term costs may be greater than if a new, more appropriate, facility were built.[17]

On the other hand, any investments in new facilities, such as a new launch complex, must also be weighed against the expected savings to be gained over the expected life of the launch system. If the up-front costs are great enough, they could outweigh the total operational costs for current systems, even if some reductions in operations costs are achieved. However, because facilities become obsolete and equipment wears out over time, and must be replaced, opportunities will arise for making program changes in the course of replacing outdated facilities. Program changes that require either major alterations, or replacement of otherwise usable launch facilities, may lead to greater life-cycle costs. Because they involve projects requiring considerable manpower, the construction and geographical placement of new facilities may also face political constraints that affect life-cycle costs.

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[16] National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technology Study," KSC Report NAS10-11344, Boeing Aerospace Operations Co., May 4, 1987, p. 4.

[17] In addition, many replacement parts required for certain Shuttle test or training systems are no longer being manufactured and must be custom built or refurbished by NASA.

Old Systems That Need Upgrading.—Because the United States decided in the early 1980s to phase out ELVs and depend solely on the Shuttle for launch services, needed improvements to the efficiencies of ELV launch fleets and facilities were not made. Many of these improvements, including performance upgrades, lighter and more capable avionics packages, and higher performance, safer solid rocket motors, are being made today as part of the Air Force's competitive ELV purchases.

Because certain parts of the Shuttle system are now more than a decade old, they need to be upgraded as well. For example, both the Shuttle's flight computers and the Shuttle processing system computers are being replaced. These changes are unlikely to lead to cheaper operations, though they will increase the capability of the Shuttle system and may contribute to greater reliability.

Excessive Documentation, Oversight, and Paperwork.—As one workshop participant charged, "it is the Government's excessive oversight and documentation that have kept the cost of space launch management and operations outrageously high." Both the Government and the contractor incur high costs from extra oversight personnel and from reporting requirements such as the Cost and Schedule Reporting System (C/SCSC). Although this system can provide useful information for reducing costs, "it must be tailored to the program and its true cost to administer must be carefully weighed against its advantages."[18]

Excessive Government oversight and reporting requirements generally develop incrementally as a response to real problems of quality control, a concern for safety, and the desire to complete high cost projects successfully. Over time these small increments of personnel or paper build to the point that they impede efficient operations, limit contractor flexibility, and add unnecessary costs.

Chapter 4 discusses several technological options for reducing the paperwork burden through installation of automated systems. It also examines the inefficiencies introduced by excessive oversight of contractors during the launch process.

Uniqueness of Launch Pad and Other Facilities.—Current U.S. facilities are often unique to a given launch system, and therefore different facilities cannot be shared. It may be possible to design future launch pads to accommodate several different launch vehicles in order to save on facilities costs. For example, the Aerospace Corporation has explored the potential of using a universal launch complex, which would be designed with a universal launch stand, a universal mobile launch platform, and a modular assembly integration building.[19] A modular integration building, in which a variety of vehicle designs can be assembled and integrated, is particularly important. However, such designs would represent a major change in the way the United States manages its launch operations and would require strong interaction between launch vehicle designers and facilities planners. These changes in operations procedures would also mark a step toward establishing launch operations that functioned more like airline operations.

Lack of Sufficient Incentives for Lowering Costs.—The current institutional and management structure provides few incentives for reducing costs of launching the Shuttle or ELVs for Government payloads. "The system does not have incentives built in for achieving low-cost, successful launches," observed one workshop participant. "There is the incentive not to fail, but not the incentive to lower costs." Several participants noted that NASA lacked the administrative structure for tracking funds and responsibilities by item to reward managers directly for reducing costs and increasing efficiency. Participants also pointed to the fact that although it is possible to fashion incentives for top-level management, it is difficult to make suitable incentives "transfer down to the guys who do the work" on the launch pad.

A recent study echoed these points and found that contractors generally have little incentive to reduce costs because "their profit/cash flow is reduced when they perform under budget." In addition, the program officers "do not have an incentive to reduce spending below the program budgeted amount."[20]

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[18] *Space Systems and Operations Cost Reduction and Cost Credibility Workshop: Executive Summary* (Washington, DC: National Security Industrial Association, January 1987), p. 2-5.

[19] U.S. Air Force, "Strategic Defense Initiative Launch Site Considerations," Report No. TOR-0084A(5460-04)-1 (Los Angeles, CA: Air Force Space Division, July 1985).

ISSUE D: What Impediments To Reducing Operations Costs Are Unique to the Space Shuttle?

The complexity of Shuttle and payload processing, and crew training, require substantial annual investment in personnel and facilities. The following points illustrate the most important impediments to reducing the costs of Shuttle launch and mission operations:

- *Shuttle still in development.*—Although NASA declared the Shuttle system operational after the fourth flight, it has as yet not achieved true operational status.[21] Because the Shuttle is still undergoing major design changes, it requires a larger launch operations staff than an "operational"[22] system. For example, NASA employs about 5000 engineers at KSC, Marshall Space Flight Center, and JSC who work on Shuttle systems. They have strong incentives to implement changes for increasing safety and performance, many of which increase the time and cost of preparing Shuttle for flight. On the other hand, there are few incentives for increasing operations efficiency and reducing costs.
- *Safety requirements.*—Because the Shuttle carries human crews, and because it is a highly visible symbol of American technological prowess, safety issues receive unusually great attention. As a result of the investigation of Shuttle subsystems following the loss of Challenger and its crew in January, 1986, the Shuttle system is now undergoing many major safety-related changes,[23] which have led to considerable system redesign. These changes have also increased the time and complexity of launch operations. Prior to the loss of Challenger, NASA had reduced the turnaround time necessary to prepare the Shuttle orbiter for flight to about 55 workdays (three shifts a day).[24] NASA expects orbiter turnaround for the first few flights to equal about 150 workdays, decreasing to an average 75 workdays only after 4 years of additional experience.[25] However, judging from the experience in preparing Discovery for the first reflight of the Shuttle since the Challenger explosion, this sort of turnaround may be extremely difficult to achieve.
- *Lack of spares; cannibalization of orbiter parts.*—The Shuttle program has had a continuing problem maintaining a sufficient stock of major spare parts and subsystems. For example, 45 out of 300 replacement parts needed for Challenger on mission 51-L had to be removed from Discovery.[26] This has significantly impeded the ability of launch crews to refurbish and test Shuttle orbiters between flights. Each time a part must be taken from one orbiter to substitute for a defective part in another, the amount of labor required more than doubles (table 2-5). In addition, the process increases the chances of damaging either the part or the subsystem from which it is removed. Although NASA has improved its stock of spares for the Shuttle, the budget allocated for spares continues to be a target for reductions. NASA runs a continuing risk of having to cannibalize parts from one orbiter to process another.
- *Complexity of the Shuttle systems.*—The Shuttle was a revolutionary step in launch systems, and was not designed for operational simplicity. As with experimental aircraft, many of its systems are highly complex, and made up of a multitude of parts

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[20] *Space Systems and Operations Cost Reduction and Cost Credibility Workshop: Executive Summary* (Washington, DC: National Security Industrial Association, January 1987), p. 2-2.

[21] George E. Mueller, Panel discussion, *Space Systems Productivity and Manufacturing Conference IV* (El Segundo, CA: Aerospace Corp., August 1987), pp. 232-235.

[22] The term "operational" implies that the vehicle in question is capable of being launched routinely on a well-defined schedule with a minimum of unplanned delays.

[23] Major alterations include improvements to the SRBs, modifications of the SSMEs, and installation of an escape hatch in the orbiter.

[24] This does not include time the orbiter spends in the Vehicle Assembly Building and on the launch pad.

[25] Charles R. Gunn, "Space Shuttle Operations Experience," paper presented at the 38th Congress of the International Astronautical Federation, Oct. 10-17, 1987.

[26] Report of the Presidential Commission on the Space Shuttle Challenger Accident (Washington, DC: U.S. Government Printing Office, 1986).

Table 2-5.—Steps in the Changeout of Defective Parts in the Shuttle Orbiter When Replacement Spares Are Unavailable

A part is needed for orbiter A. It is not in the parts inventory, but is available in orbiter B, which is not scheduled to fly for several months. The following steps are necessary:

+ **Document steps of part's removal from orbiter B.**
+ **Remove part from orbiter B. (It takes longer to remove a part from an orbiter than to take it from storage.)**
Document installation in orbiter A.
Install the part in orbiter A.
Test part in orbiter A.
+ **Document installation of replacement part in orbiter B.**
+ **Install replacement part in orbiter B.**
+ **Test replacement part in orbiter B.**

+ = Addition to standard procedure.

SOURCE: Office of Technology Assessment, 1988.

that need to be inspected or repaired.[27] For example, each of the solid rocket boosters (SRBs), one of the simpler Shuttle elements, contains about 75,000 parts and components. Of these, about 5,000 are removed, inspected, and replaced or refurbished after each Shuttle flight. A design that required inspecting and handling of fewer parts would require fewer launch personnel. However, the costs of redesign, testing, and acceptance of such a simplified design must be taken into account.

The thermal protection system, composed of over 31,000 fragile tiles, requires careful inspection and repair, an extremely labor intensive operation. Although only about 50 tiles now need replacing because of damage after each flight, all of them must be inspected.[28] Not only must they be inspected for damage, they must also be tested for adherence to the vehicle, and the gaps between tiles carefully measured to assure sufficient space for thermal expansion upon reentry. (See ch. 4, box 4-A for a description of a semi-automated system for inspecting and replacing the TPS.)

Finally, the Shuttle orbiter has about 250,000 electrical connections which must be tested for continuity. Each time one of the 8,000 connectors is disconnected or removed, there is a chance that one or more pins will be damaged or will otherwise fail to reconnect properly.

ISSUE E: What Can the Operational Experience of the Airlines Contribute to Space Operations?

Although the technical and managerial constraints on airlines operations are quite different than for launch vehicles, certain of their methods used in logistics, maintenance, task scheduling, and other ground operations categories may provide a useful model for making launch operations more efficient and cost-effective. Because of the extreme volatility of launch propellants and a relatively low launch rate, other airlines methods may not be applicable to launch or mission operations. Chapter 4 discusses the specific applications of airline operations practices to space operations. Many of these lessons are being applied in the Advanced Launch System program (see ch. 4). The airlines:

- *. . . begin cost containment program at planning stage.*[29] New aircraft design takes into account operational requirements such as support equipment, logistics flow, and facility design, as well as payload characteristics and route structure, in the early planning stages.
- *. . . involve operations personnel in design changes.* As one workshop participant observed, "the chief objective of the airlines is to move a seat from A to B as quickly and efficiently as possible. Safety is a primary goal, but increased efficiency is a basic requirement for making any design change." Increases in efficiency must outweigh any shortcomings brought about by incorporating such a design change in the entire system.

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[27] George E. Mueller, "Panel on Productivity Issues for Space and Launch Systems," *Space Systems Productivity and Manufacturing Conference IV* (El Segundo, CA: The Aerospace Corporation, 1987), pp. 232-35.

[28] Only a few tiles are interchangeable; most are unique three dimensional shapes that are fitted to the curved surfaces of the orbiter. Charles R. Gunn, "Space Shuttle Operations Experience," paper presented at the 38th Congress of the International Astronautical Federation, Oct. 10-17, 1987, p. 2.

[29] "Space Systems and Operations Cost Reduction and Cost Credibility Workshop," Executive Summary (Washington, DC: National Security Industrial Association, January 1987), pp. 2-18 - 2-19.

- . . . *have developed detailed cost estimating relationships for operations.* When an aircraft manufacturer suggests improved equipment for an aircraft subsystem, the airline can generally estimate the recurring and nonrecurring costs and any potential savings to be gained. The airlines also have an extensive historical database to assist them in testing the accuracy of their own cost estimation models.
- . . . *stand down to trace and repair failures only when the evidence points to a generic failure.* Generally the airlines continue flying when one aircraft has crashed unless there is clear initial evidence of a generic fault in the aircraft model. For example, in the November, 1987 crash of a DC9 in a Denver snowstorm, other DC9s continued to fly. However, in the 1979 crash of a DC10 in Chicago, the entire DC10 fleet was grounded because there was early evidence that the wing mounting of one of the engines had failed, and safety officials were concerned that generic structural faults might have caused the failure.
- . . . *insist on aircraft designed for fault tolerance.* Commercial aircraft are designed to be robust enough to fly even when they have known faults. Airlines, with thousands of flights per day, have developed a minimum-equipment list—a list of vital operations equipment that is absolutely mandatory for flight; if any of this equipment malfunctions on pre-flight check-out, the plane is grounded until the problem is fixed. The existence of such a list means that an aircraft can fly with known faults as long as they are not on the minimum equipment list.
- . . . *design aircraft for maintainability.* Commercial airliners are designed to be inspected periodically and to have certain parts and subsystems pulled and inspected after a given number of hours of flight. The airlines call this practice "reliability-centered maintenance."
- . . . *encourage competitive pricing.* For the manufacturers of aircraft and aircraft subsystems, the ability to purchase competitive systems from several suppliers acts as an incentive not only to reduce costs, but to improve reliability.
- . . . *maintain strong training programs.* In the airlines, at all times some 10 percent of the operations crews are in training. Training includes all aspects of the operations procedures. Extensive training contributes to flight safety as well as to lowering costs.
- . . . *use automatic built-in checkout of subsystems between flights.* Many aircraft subsystems can be checked from the cockpit or from mobile ground units between flights, and in some cases, even in-flight with the aid of ground-based data links. Because they involve minimum operator interaction, these procedures tend to be more accurate than non-automated systems.

ISSUE F: Does the United States Possess Adequate Techniques To Judge the Relative Benefit of Improvements in Launch and Mission Operations Procedures?

When debating the relative merits of either improving current launch systems or developing a major new one, the principal question for Congress is: will the investment in a new system be worth it? In other words, will spending more money now yield greater savings later in the life cycle of a system? Answering this straightforward question is impossible without adequate models for estimating costs. OTA workshop participants generally agreed the United States has not developed adequate cost estimating models for launch and mission operations procedures.

Workshop participants noted that estimating costs of new or improved systems requires data from existing systems. Commercial airlines use extensive historical data to help them create accurate models for estimating costs, but launch operations do not have a comparable database to draw upon. In addition, NASA and the Air Force have made no focused effort to collect such information. For example, there are no detailed historical records tracing the number and cost of personnel for different components of space operations. One reason is that this information, where gathered, often rests with the contractors, who regard it as proprietary. In addition, for systems in development, the technologies tend to be more fluid, and therefore operations data that could be collected are poor predictors of the applicable costs for later routine launches. A deeper reason is that the funding required to gather and analyze such historical data is often the first thing to be eliminated from a program to save money—"but what is being eliminated is the future capability to learn from mistakes," stated one workshop participant. Today we do not have sufficient data on which to base a more meaningful cost estimation model.

STAS contractors focused some effort on cost modeling, but their work was hampered by inadequate historical data. In addition, the accuracy of cost models developed by the contractors awaits validation. The ALS Phase 1 study teams have continued work on developing better cost models.

What is often unclear in policy debates over the choice of a new space transportation system is that estimating the costs of ground operations is necessarily uncertain and partially subjective. Program managers often fail to calculate and present to policymakers the uncertainties in estimated costs. New cost models will reduce the uncertainty and subjectivity of cost estimation but not eliminate them. If such uncertainties and subjective judgements were made more explicit, it would be possible to give policy makers a clearer sense of the economic risks of alternatives.[30]

Appendix A contains a brief summary of current cost estimation methods that illustrates the uncertainty and subjectivity involved. Methods used in the Space Transportation Architecture Study (STAS) are typical and are used as examples.

ISSUE G: Are the Near-Term Launch Systems Under Study by NASA and the Air Force Likely To Generate Major Reductions of Launch Operations Costs?

The goal of the Advanced Launch System (ALS) program is to design a low cost, heavy lift launch system to serve U.S needs at the turn of the century.[31] Chapter 4 examines many of the operations technologies under study in the ALS program. However, because an ALS would require some technologies not fully developed at this time, and because NASA and the Air Force would like to be prepared to meet any additional demand for launch services in the mid 1990s, they are also considering options for new, interim, high capacity launch systems based on current technology.[32]

The following paragraphs discuss the launch operations requirements of two options, one based on Shuttle technology, the other based on a variety of other technologies, and explores whether they would lead to reduced operational costs. OTA's analysis of these proposed systems leads to the general conclusion that although careful design, which took into account the operational requirements of such systems, could indeed reduce operating costs, the investment cost of adding the necessary operations infrastructure and its attendant recurring costs might offset such gains, especially if launch demand remains low. Policy makers should carefully scrutinize estimated life-cycle costs of any new system.

Shuttle-C (Cargo Vehicle)

NASA's version of a heavy-lift launch vehicle is the Shuttle-C, which in several respects competes with Air Force heavy-lift concepts. The Shuttle-C[33] would be an unpiloted cargo vehicle based primarily on Shuttle technology. It would use the solid rocket boosters, the external tank, and the main engines (SSMEs) from the Shuttle system. A large cargo canister, capable of transporting some 85,000 to 100,000 lbs. of payload to low-Earth orbit, would take the place of the current Shuttle orbiter.[34] If Shuttle-C is used to ship major subassemblies of the space station to orbit, one Shuttle-C flight would replace two or three Shuttle missions. These could reduce the need to fly all of NASA's planned shuttle missions.

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[30] T. Mullin, "Experts' Estimation of Uncertain Quantities and Its Implications for Knowledge Acquisition," *IEEE Transactions on Systems, Man, and Cybernetics* [to be published].

[31] The program's original goal was to design a heavy-lift launch system that would serve U.S. needs at the turn of the century, resulting in a so-called "objective" system, with an "interim" system based on existing technologies for the mid 1990s. However, congressional resistance to funding a system capable of launching a space-based ballistic missile defense system caused Congress to forbid expenditures for studies of an interim ALS system.

[32] See U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988), ch. 4.

[33] Ibid.

[34] STAS also considered in-line Shuttle-derived vehicles, but these are considered to require too much development to be considered as a low-cost alternative at the present time.

Shuttle-C would have the advantage of using much of the same technology and many of the same parts that have already proved successful in 24 flights. To keep fixed costs down, it would use the same launch pads, vertical integration facilities, and launch support crews now used for the Shuttle. It carries the disadvantage that a stand down of the Shuttle might well result in delaying Shuttle-C flights for the same reasons.

However, the following considerations would affect the costs of launch operations for the Shuttle-C:

- Not having to process a Shuttle orbiter would likely speed up launch operations and therefore reduce total operations costs compared to the Shuttle.[35] However, it would still be necessary to assemble, integrate, and test the Shuttle-C before flight. In addition, some Shuttle-C designs call for employing a reusable engine/avionics package that would need to be refurbished after each flight. If the Shuttle-C were not specifically designed for simplicity and ease of operation, its operational costs could grow to become a significant fraction of the cost of preparing the Shuttle orbiter.
- Shuttle-C will affect the processing flow of the Shuttle orbiter. Because the Shuttle-C would be the same overall size and configuration as the Shuttle, it could be processed in the same facilities as the Shuttle, and inserted into the Shuttle flow, if the Shuttle launch schedule permits. This raises several cost-related issues.

  First, because NASA intends to use Shuttle-C for transporting major components of the space station to orbit, which are likely to be of substantially greater value than the vehicle, NASA would have considerable incentive to process the Shuttle-C as carefully as it processes the Shuttle, and with the same crews and procedures.[36]

  Second, the Shuttle facilities themselves, including the launch pads, may constrain NASA's ability to reach the 12-14 launches per year projected for a 4-orbiter fleet, and simultaneously launch Shuttle-C two or three times a year. Launching both vehicles requires either shifting some payloads, such as space science missions, to the Shuttle-C and flying fewer orbiter missions, or building new facilities to accommodate Shuttle-C. New or upgraded facilities might include increased engine shop facilities, an engine/avionics processing facility, and a mobile launch platform. Any necessary new facilities should be taken into account when costing the Shuttle-C system.[37]

  Inserting Shuttle-C into the Shuttle processing flow could actually increase costs for launching the orbiter because of the risk of slipping Shuttle-C schedules. Experience has shown that nonstandard tasks, such as engineering modifications or special instrumentation, imposed on the Shuttle processing flow can contribute as much as 50 percent to an orbiter's turnaround time.[38] Because, except for the orbiter, Shuttle-C hardware would be quite similar to Shuttle hardware, we should expect Shuttle-C to experience similar delays for several years after being introduced into NASA's fleet. Modifications to non-orbiter Shuttle subsystems would have to be made on the Shuttle-C as well.

  Finally, because Shuttle-C would share many parts with the Shuttle, delays may occur in one or the other launch system should the parts supply system become choked. On the other hand, because parts become cheaper when purchased in quantity, the existence of a Shuttle-C might reduce the costs of some parts.
- Mission Operations would be simpler and therefore less costly than for the Shuttle orbiter. Because the Shuttle-C would not carry humans, mission operations would consist

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[35] Because it takes longer than any other single ground operations procedure, processing of the Shuttle orbiter effectively sets the Shuttle launch rate.

[36] It might even cost more to develop independent launch processes for Shuttle-C because NASA would then have to train additional launch crews.

[37] Recent NASA estimates for the cost of additional facilities at KSC range from $60 to $300 million depending on the number of projected Shuttle and Shuttle-C flights.

[38] Charles R. Gunn, "Space Shuttle Operations Experience," paper presented at the 38th Congress of the International Astronautical Federation, Oct. 10-17, 1987.

primarily of control, navigation, and guidance, and releasing the payloads at the proper time and in the proper orbit.

- Payload manifesting. For non-monolithic payloads, the costs of payload manifesting and integration are likely to be comparable to the Shuttle. NASA's experience on the orbiter has shown that payloads may interact in unforeseen ways, and require considerably more testing. If payloads were required to be self-contained, as suggested for the Advanced Launch System, it might be possible to reduce some of these costs. However, because the payloads would be required to provide services normally provided by the launcher, such payloads would likely weigh much more. (See ch. 4 for a discussion of this point.)

Air Force Near-Term Launch Systems

The Air Force is considering building larger capacity vehicles to carry spacecraft designed for ongoing Air Force programs, which are slowly but steadily growing in payload mass and size as they grow more capable. Modifications to existing vehicles to increase payload capacity offer no great operations savings.[39]

A new high capacity interim launch vehicle specifically designed for rapid ground operations might reduce launch operations costs sufficiently to pay for the necessary R&D. However, this would also require high demand for launch services.[40] If high demand for cargo launch failed to materialize during 1992-1997, it would not be prudent to invest in a high capacity launch system designed to respond to high launch rate.[41] Developing a new system, even from existing technology, also incurs substantial risk that the new vehicles could not be processed for launch as quickly as planned, whether for technical or "cultural" reasons. In fact, OTA workshop participants were extremely skeptical that launch processing times could be dramatically accelerated in the near term. They argued that only if radical changes were made in the methods of launching space vehicles and the institutional culture surrounding launch processing could costs be brought down significantly.

ISSUE H: How Do Concerns for Launch System Reliability Affect Launch Operations?

The reliability of a launch vehicle (see app. C) has always been of concern to payload managers, because the cost of a payload may amount to two to eight times the cost of launch services. Although some commercial communications satellites are relatively inexpensive compared to research or national security spacecraft, companies may stand to lose potential revenue amounting to hundreds of millions of dollars if their spacecraft fail to reach orbit. Payload owners regard the incremental costs of additional procedures to increase launcher reliability, even for unpiloted vehicles, as worth the cost. The built-in conflict between the desire to reduce launch operations costs and the desire to increase the success of launching spacecraft typically results in increased attention to detail and a consequent increase in costs.

For the high visibility Shuttle, national prestige and leadership as well as safety and reliability are at stake. Losing an orbiter, or even encountering non-catastrophic failures, are blows to national prestige. Nevertheless, in the view of some launch managers, launch operations currently assume more than their share of the cost burden for improvements in the reliability of an operational system. Launch operations tend to be complex and time consuming because vehicles have been designed to achieve high performance rather than rapid, inexpensive launch turnaround, and because launch managers perceive they can improve the chances of launch success by repeatedly testing every possible subsystem before launch. Their confidence in the reliability of a launch system is generally lower than the calculated engineering estimates.[42]

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[39] The Aerospace Corp., Space Transportation Development Directorate, *Air Force-Focused Space Transportation Architecture Study* (El Segundo, CA: The Aerospace Corp., Report TOR-0086A(2460-01)-2, August 1987).

[40] The only program currently under consideration that could require this sort of payload demand is the deployment of space-based ballistic missile defenses (SDI).

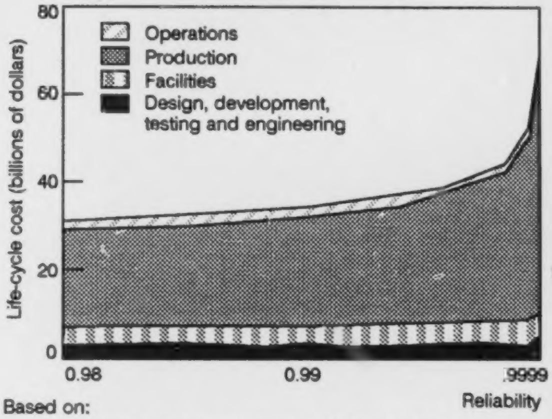
[41] See U.S. Congress, Office of Technology Assessment Special Report, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

[42] Ibid., p. 85.

Some experts argue that it may not be possible to lower overall launch costs (including the vehicle, payload, and other subsystems) significantly *without* increasing system reliability because the costs of losing launch vehicles and payloads are too high. A reusable system, especially, depends upon successful recovery and easy refurbishment of expensive components. On the other hand, the experience with recent improvements to the Shuttle system demonstrates how expensive it can be to improve a launch system's reliability. Although experts disagree about the estimated reliability of the Shuttle with these improvements, they do agree that instituting and carrying out a test program capable of substantially improving confidence in the reliability of the Shuttle is likely to be costly. Figure 2-4 illustrates the expected rapid rise in costs as engineers attempt to design vehicles for reliabilities above the 99 percent level.

Because of Titan and Shuttle launch failures in 1985 and 1986, the time it now takes to assemble, integrate, check out and launch these vehicles is much greater than before the failures. Increased emphasis on safety and subsystem testing and quality control to catch potential failures contribute most of such increases. Managers now know much more about the vehicles, though they can seldom point to a specific example of a fault that would likely have led to a launch failure unless repaired.[43]

Figure 2-4.—Cost of Achieving Extremely High Reliability



Based on:

- Expendable vehicle, 20 years of flight, 1 launch site
- 5M lb to LEO, 125K capability
- 40 flights per year, 100% load factor

SOURCE: Martin Marietta.

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[43] OTA staff were told at a briefing at Vandenberg Air Force Base in July 1987 that the non-destructive testing of Titan solid rocket motors instituted after the 1986 Titan launch failure had revealed a number of imperfections in the propellant of solid rocket motors segments, which had been stored for some time. These were reworked to eliminate such imperfections. However, it is not at all clear that they would have caused a launch failure if they had gone undiscovered.

Chapter 3

Operations Procedures

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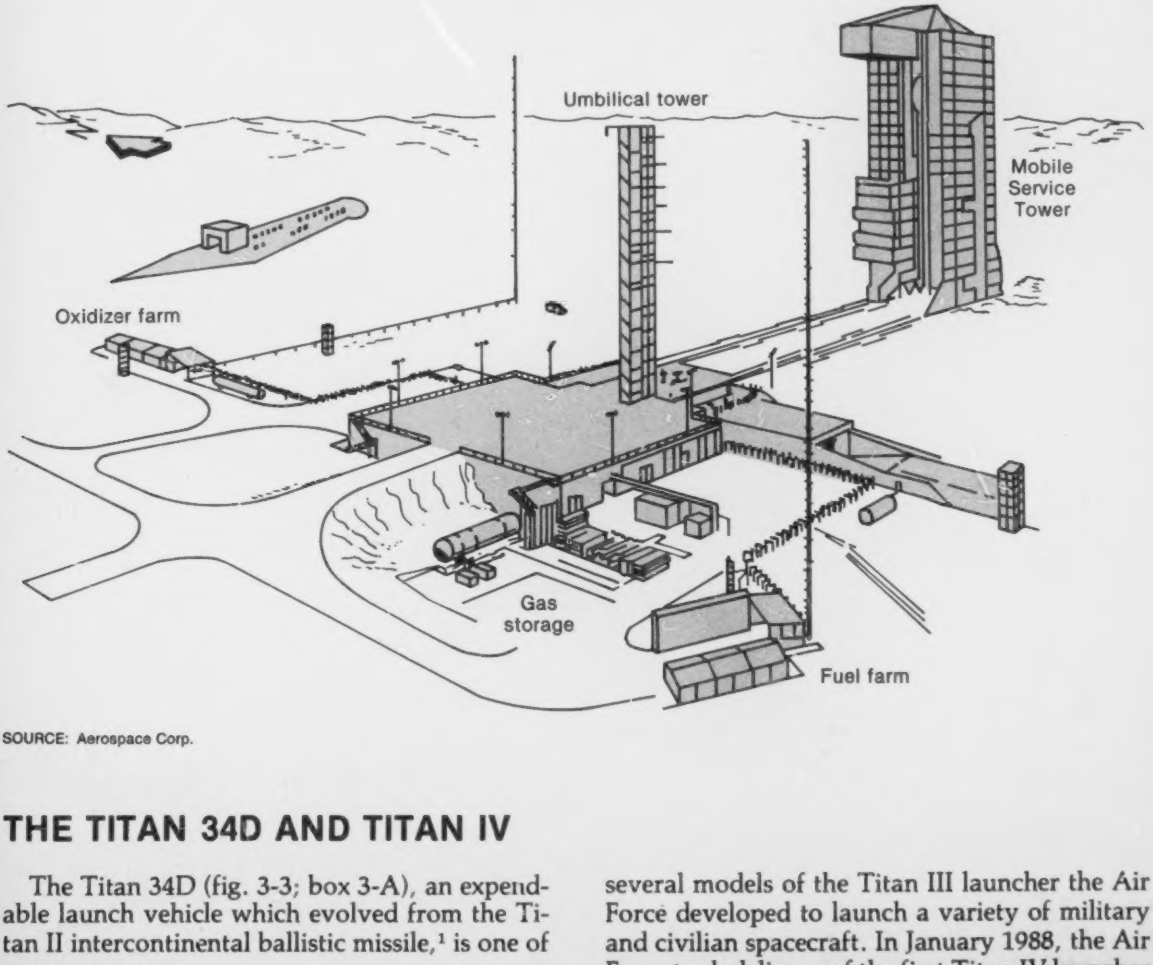
Chapter 3

Operations Procedures

Existing operations, which are enormously varied and complex, offer important lessons for the design of future vehicles. Launch operations includes all the resources required to maintain and launch space vehicles, including unique facilities, specialized equipment, computer systems, scheduling, documentation, personnel, and management techniques (fig. 3-1; 3-2). Mission operations includes all activities associated with planning and executing a mission—flight planning, documentation, mission support, and training. This chapter summarizes operations procedures and schedules as they are currently followed for the Titan and the Shuttle.

Figure 3-1.—Overview of Vandenberg Titan Launch Facilities



SOURCE: Aerospace Corp.

THE TITAN 34D AND TITAN IV

The Titan 34D (fig. 3-3; box 3-A), an expendable launch vehicle which evolved from the Titan II intercontinental ballistic missile,[1] is one of several models of the Titan III launcher the Air Force developed to launch a variety of military and civilian spacecraft. In January 1988, the Air Force took delivery of the first Titan IV launcher (fig. 3-4; box 3-A), which is larger and delivers a heavier payload to orbit than the Titan 34D.

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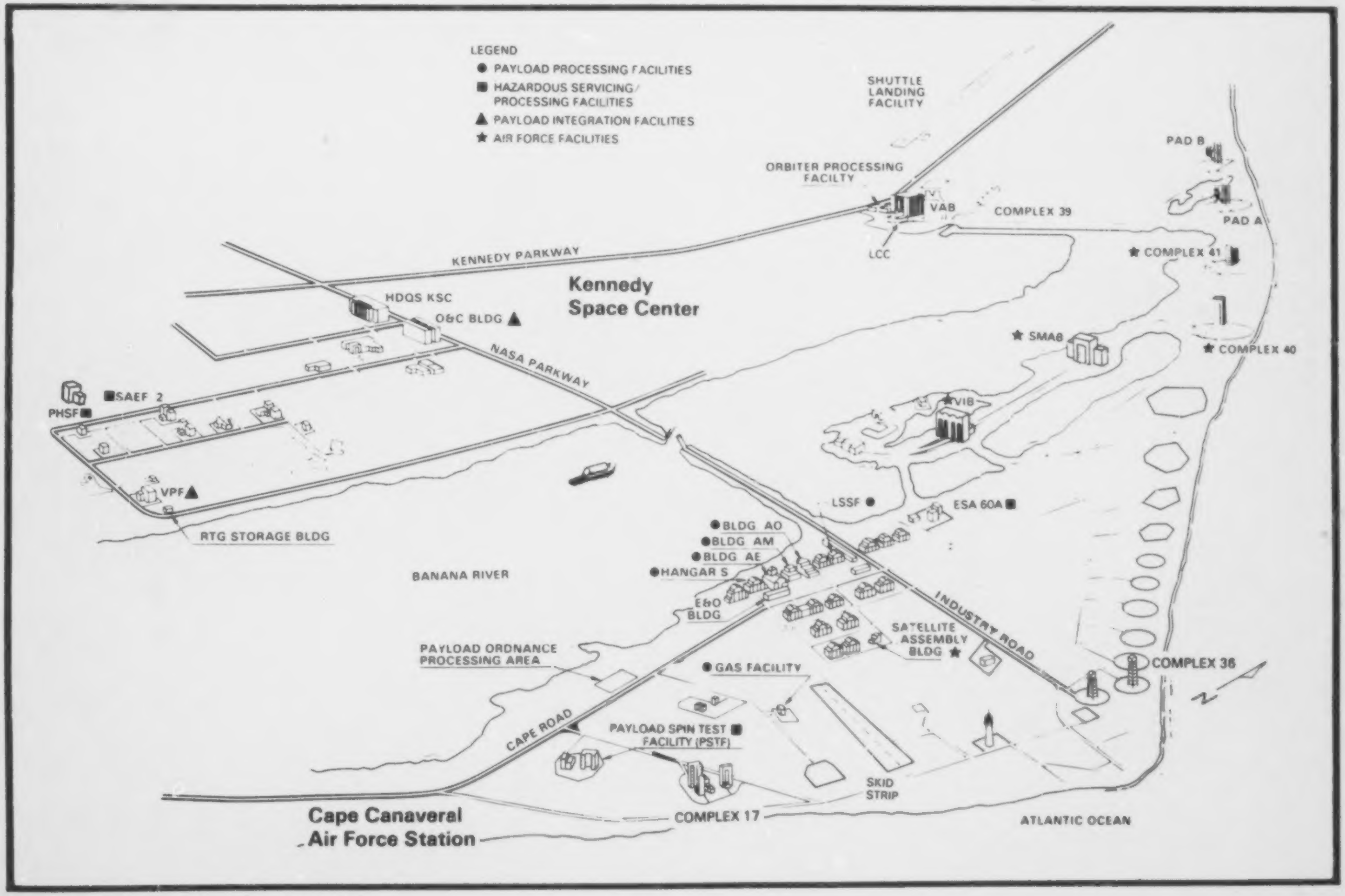
[1] A crew-rated version of the Titan II served as the launch vehicle for the Gemini program of the early 1960s.

Figure 3-2.—Kennedy Space Center Payload Facilities


LEGEND
● PAYLOAD PROCESSING FACILITIES
■ HAZARDOUS SERVICING/ PROCESSING FACILITIES
▲ PAYLOAD INTEGRATION FACILITIES
★ AIR FORCE FACILITIES
SHUTTLE LANDING FACILITY
ORBITER PROCESSING FACILTY
VAB
COMPLEX 39
LCC
PAD B
PAD A
★ COMPLEX 41
★ COMPLEX 40
★ SMAB
★VIB
KENNEDY PARKWAY
Kennedy Space Center
HDQS KSC
O&C BLDG ▲
NASA PARKWAY
■SAEF 2
PHSF■
VPF▲
RTG STORAGE BLDG
BANANA RIVER
LSSF ●
ESA 60A ■
●BLDG AO
●BLDG AM
●BLDG AE
●HANGAR S
E&O BLDG
INDUSTRY ROAD
SATELLITE ASSEMBLY BLDG ★
COMPLEX 36
PAYLOAD ORDNANCE PROCESSING AREA
● GAS FACILITY
CAPE ROAD
PAYLOAD SPIN TEST ■ FACILITY (PSTF)
SKID STRIP
COMPLEX 17
ATLANTIC OCEAN
N
Cape Canaveral Air Force Station

SOURCE: National Aeronautics and Space Administration.

Box 3-A.—Titan 34D and Titan IV Launch Systems

The Titan 34D Vehicle

The Titan 34D is an expendable launch vehicle developed by Martin Marietta Corporation under contract with the Air Force. It is capable of launching up to 4,000 pounds of payload into geosynchronous orbit, or 30,000 pounds of payload into low earth orbit (LEO), and is now available commercially.[1] It consists of a two-stage liquid-fuel rocket core vehicle, which carries the payload, and two strap-on solid-fuel rocket motors.[2]

The solid-fuel rocket motors,[3] which are 122 inches in diameter and 90.4 feet long, develop about 1.4 million lb. thrust each. They are similar in construction to the solid-fuel rocket boosters for the Shuttle (though they rely on a different design for the seals between segments), and are built up of 5 individual segments.

The Titan IV Vehicle

The Titan IV expendable launch vehicle is the latest in the Titan family of launch vehicles. Developed by Martin Marietta Corporation under contract to the Air Force, the Titan IV uses the same fuels and subsystems as its sister vehicle, and provides the lift and cargo capability of the Space Shuttle. It is capable of launching 10,000 pounds of payload into geosynchronous orbit, or 39,000 pounds into low earth orbit, using the Centaur upper stage.

The overall design is similar to the Titan 34D but its core vehicle has been lengthened approximately 20 feet to carry more liquid propellant. The solid rocket motors have been increased to seven segments. Recently, Martin Marietta selected Hercules Aerospace Co. as an additional supplier of solid rocket boosters for the Titan IV.[4] These boosters will provide a 25 percent increase in payload capacity. The Air Force and Martin Marietta have developed three major versions of the Titan IV: a No Upper Stage (NUS), an Inertial Upper Stage (IUS), and a Centaur Upper Stage (Centaur).

Generic Titan Systems

The valves, ignition system, guidance system, and all the other systems aboard both launchers are controlled either by avionics located in the second stage of the core vehicle, or by telemetry from the ground. Guidance signals for the avionics complement are generated in the upper stages. The launch complexes and associated facilities are similar for both vehicles; they differ primarily in size.

Typically, a Titan 34D launch costs about $90 to $110 million including launch services. Launch services account for 12 to 20 percent of the total cost, depending on the extent and complexity of services required. A Titan IV launch costs $120 million, including launch services.

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[1] In 1987, Martin Marietta formed a subsidiary corporation, Commercial Titan, Incorporated to market Titan launch services. Martin Marietta has negotiated with the Air Force to use launch complex 40 at Cape Canaveral (for a fee) for commercial launches. Andrew Wilson, "Titan Grows Stronger," SPACE, vol. 3, pp. 8-11, 1987.

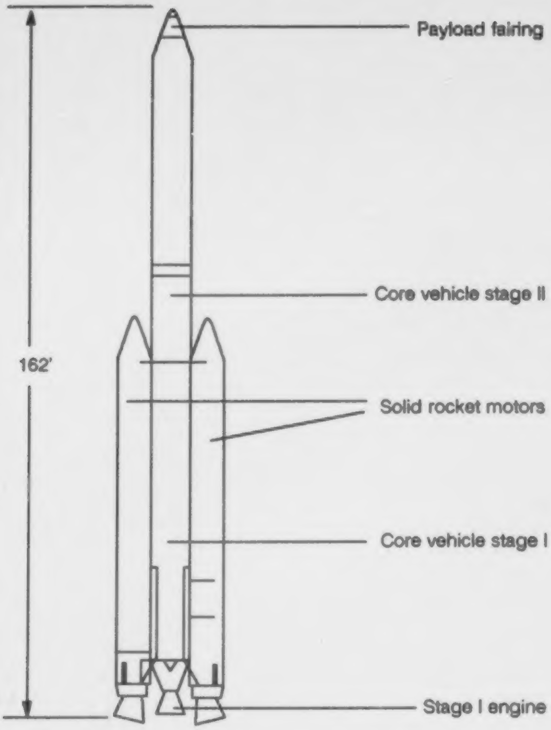
[2] Built by Chemical Systems Division, United Technologies Corp. It supplies similar, larger solid rocket boosters for the Titan 4.

The propellant in the core vehicle is hypergolic, meaning that the fuel (Aerozine-50) and the oxidizer (nitrogen tetroxide) ignite on contact and therefore need no ignition system; at the right moment during the countdown, computers at the launch control center direct fuel valves to open, allowing the two fluids to mix. Turbopumps feed the liquid fuel engines, which are hydraulically gimbaled for steering.

[3] The propellant is a mixture of powdered aluminum, ammonium perchlorate, synthetic rubber, and various additives. The recent explosion at one of the Nation's two ammonium perchlorate plants has caused a severe shortage of the chemical for boosters.

[4] See "Hercules Wins Contract for Titan 4 SRM Work," *Aviation Week and Space Technology*, Oct. 26, 1987, p. 31.

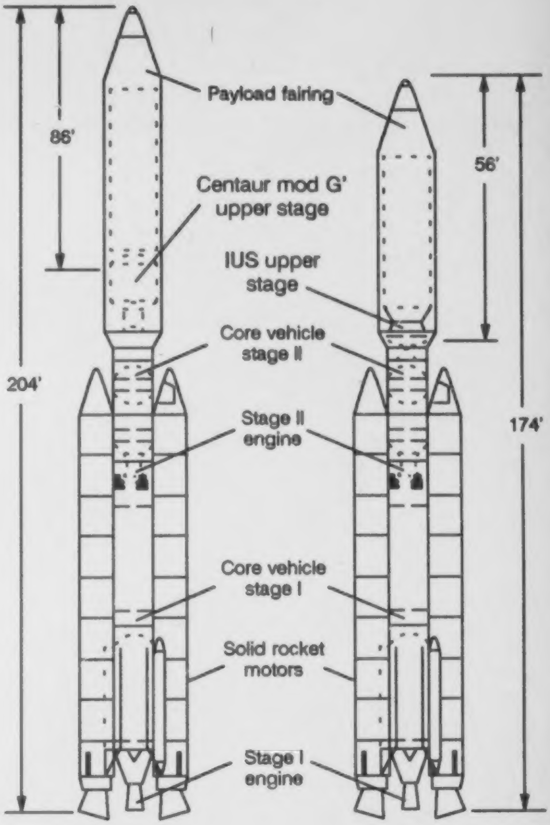
Figure 3-3.—Titan 34D Launcher


Payload fairing
162'
Core vehicle stage II
Solid rocket motors
Core vehicle stage I
Stage I engine

SOURCE: Martin Marietta.

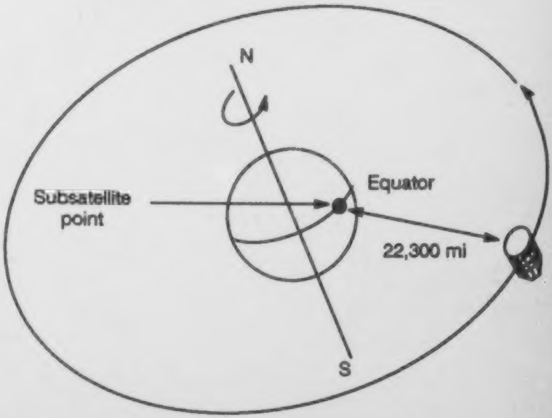
The Air Force maintains two Titan launch complexes at Cape Canaveral Air Force Station, Florida, and two at Vandenberg Air Force Base, California. As the result of their geographical location at 28° north latitude, the East Coast launch complexes are used for launching payloads toward the East into low inclination and geosynchronous orbits (fig. 3-5). The West Coast launch complexes are used for launching payloads south into high inclination orbits, such as sun-synchronous, polar orbits (fig. 3-6).

Figure 3-4.—Titan IV Launcher


86'
204'
Payload fairing
Centaur mod G' upper stage
IUS upper stage
Core vehicle stage II
Stage II engine
Core vehicle stage I
Solid rocket motors
Stage I engine
56'
174'

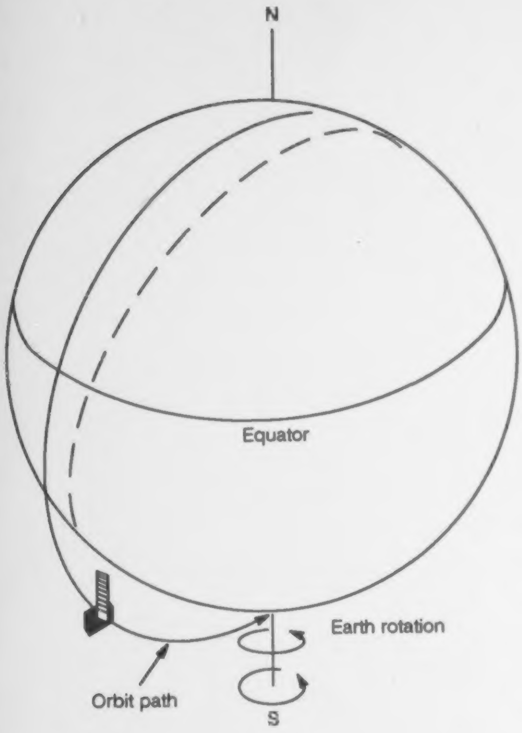
SOURCE: Martin Marietta.

Figure 3-5.—Geosynchronous Orbit


N
Subsatellite point
Equator
22,300 mi
S

SOURCE: Office of Technology Assessment, 1988.

Figure 3-6.—High Inclination Orbit



SOURCE: Office of Technology Assessment, 1988.

Launch Operations—Cape Canaveral[2]

Contractors[3] assemble and prepare the launch vehicle and payloads, monitored by Air Force personnel (figs. 3-7 and 3-8). At Cape Canaveral, the launcher is prepared and launched following a modified integrate-transfer-launch procedure (ITL),[4] in which the launch vehicle is assembled in the Vertical Integration Building and Solid Motor Assembly Building, and wheeled out to the launch complex on a transporter (fig. 3-9). Other procedures, such as stacking of the solid rocket motors, can be carried out in parallel while the core vehicle is assembled and tested. This technique minimizes the amount of time the vehicle must remain on the launch pad.

At Cape Canaveral, the ITL concept makes it possible to sustain about four Titan launches per year from each of two pads (pad 40 and 41). The addition of some new facilities and upgrades of existing facilities would enable six to eight launches from each pad. Currently, the Air Force plans to launch approximately six vehicles per year from the East Coast. Martin Marietta expects to launch an additional three commercial vehicles per year from pad 40 at Cape Canaveral.

The average time from receipt of launcher components and payload at Cape Canaveral to launch is 5 to 9 months, depending on the complexity of the vehicle desired.[5] The Air Force expects each Titan IV to spend 8 to 9½ weeks on the launch pad, and each commercial Titan 34D about 6 weeks.

Launch operations begin with the arrival of the parts of a launch vehicle, by rail, truck, and aircraft.

Solid Rocket Motors

Solid-fuel rocket motor segments and other solid rocket booster parts arrive at the launch center by rail. After inspecting the parts visually, technicians inspect the propellant-filled motor segments for internal manufacturing flaws in the Non-destructive Test Facility.[6] These items are

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[2] Much of the data for this section was supplied by the "Spacecraft Users Guide," Martin Marietta, April 1982.

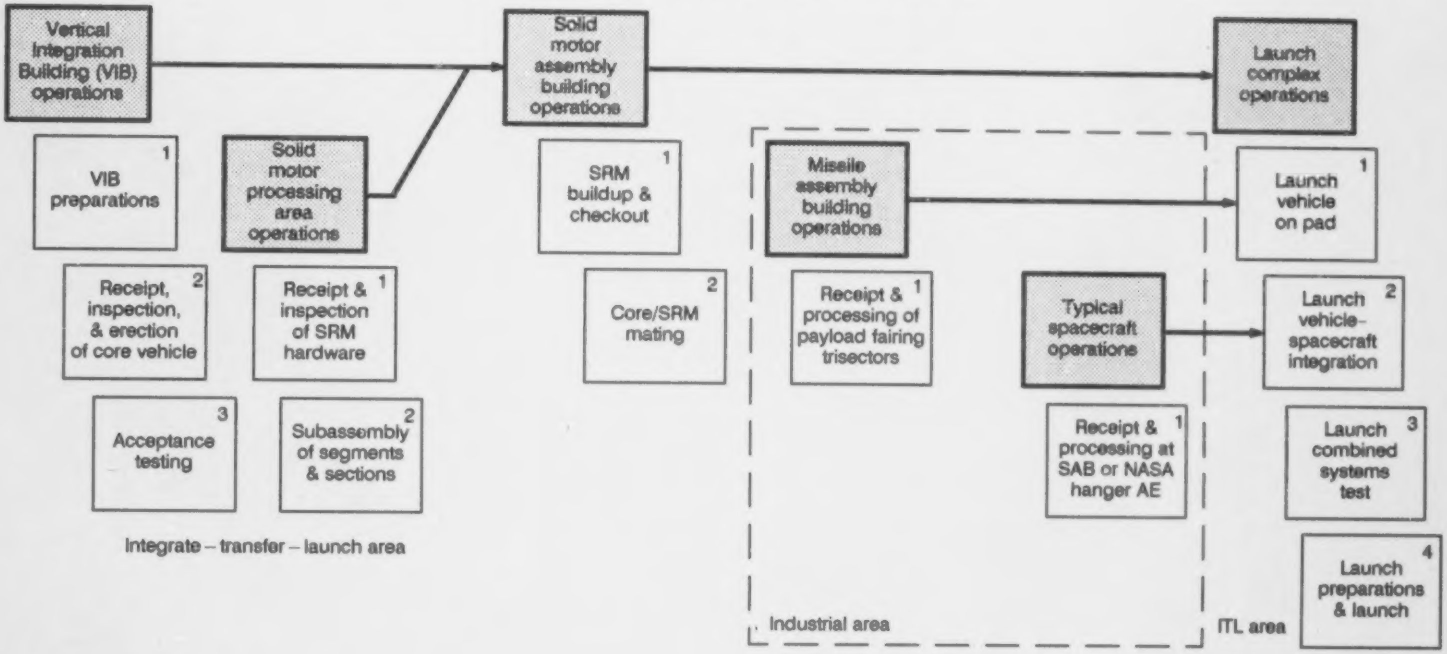
[3] Martin Marietta, which builds the Titan launch vehicle, is the principal contractor. Other major contractors involved in the launch process include the Chemical Systems Division of United Technologies (solid rocket motors), McDonnell Douglas (payload fairing), Boeing (Inertial Upper Stage), and General Dynamics (Centaur Upper Stage).

[4] The Cape Canaveral launch complex was originally designed to support up to 60 launches per year. However, it has never reached that productivity goal, in part because launch procedures have grown more complicated and require a greater number of facilities than are available. In addition, high demand for launches never materialized. See chs. 4 and 5 for additional details.

[5] Assembly and checkout of the Titan IV is likely to take several weeks longer than the Titan III because Martin Marietta is doing most of the initial assembly at Cape Canaveral rather than the factory in Denver.

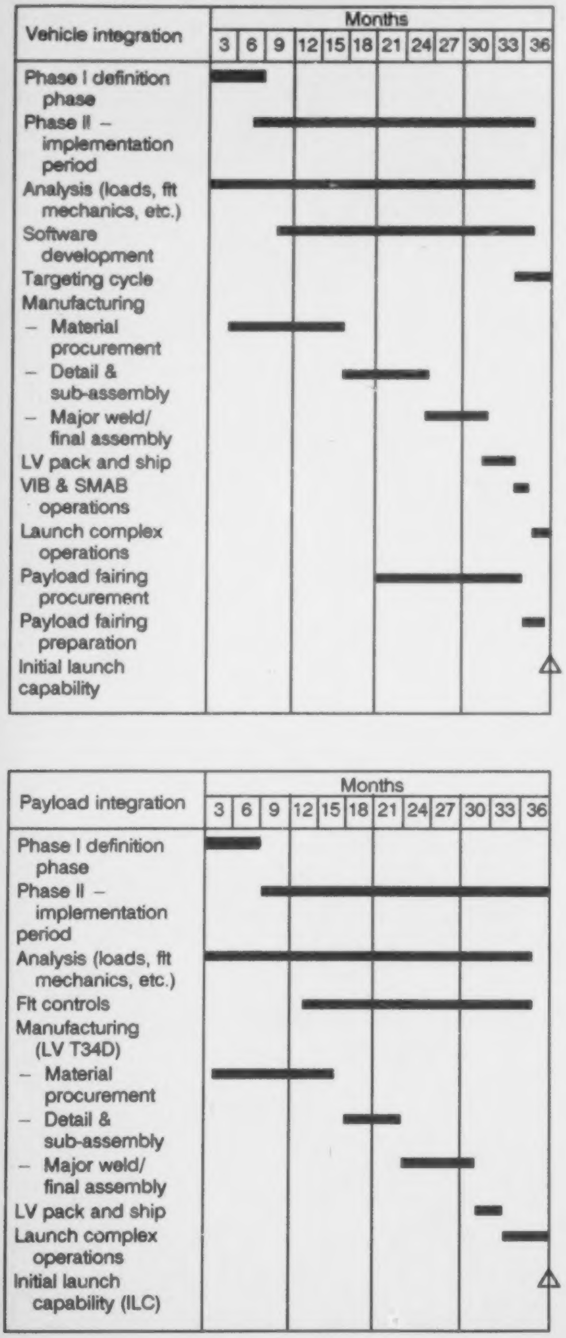
[6] After a Titan 34D exploded 8.5 seconds into flight on April 18, 1986, the Air Force launched a detailed investigation into the cause of the failure. After discovering that the failure was likely the result of debonding of the insulation within the Titan solid rocket motor (see "Titan Solid Booster Failure Caused Vandenberg Accident," *Aviation Week and Space Technology*, May 5, 1986, pp. 24-5), the Air Force developed an extensive non-destructive inspection program to qualify the booster segments. It also included additional sensors to monitor launcher systems. See "Titan Mission Success Based on Tighter Heavy Booster Standards," *Aviation Week and Space Technology*, Nov. 2, 1987, pp. 25-6.

Figure 3-7.—Typical Titan Receipt-to-Launch Flow


Vertical Integration Building (VIB) operations
1 VIB preparations
2 Receipt, inspection, & erection of core vehicle
3 Acceptance testing
Solid motor processing area operations
1 Receipt & inspection of SRM hardware
2 Subassembly of segments & sections
Integrate – transfer – launch area
Solid motor assembly building operations
1 SRM buildup & checkout
2 Core/SRM mating
Missile assembly building operations
1 Receipt & processing of payload fairing trisectors
Typical spacecraft operations
1 Receipt & processing at SAB or NASA hanger AE
Industrial area
Launch complex operations
1 Launch vehicle on pad
2 Launch vehicle-spacecraft integration
3 Launch combined systems test
4 Launch preparations & launch
ITL area

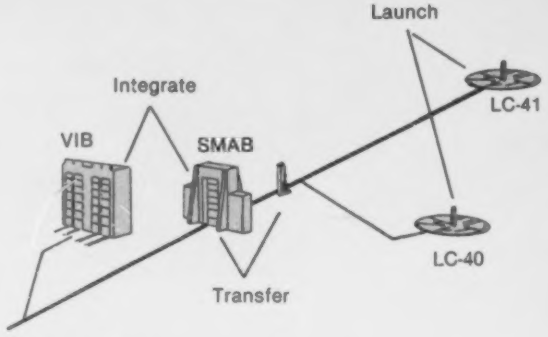
SOURCE: Martin Marietta.

Figure 3-8.—Typical Titan Launch Schedule, Cape Canaveral



SOURCE: Martin Marietta.

Figure 3-9.—Titan Integrate/Transfer/Launch



SOURCE: Martin Marietta.

transported to the Solid Motor Assembly Building (SMAB), where they are stored. In the SMAB, the contractor erects the solid rocket boosters, beginning with the the aft subassembly. Electrical cabling and other supports are installed, as well as emergency-destruct explosive charges.

Core Vehicle

Concurrently, the two stages of the core vehicle are inspected and assembled atop the launch vehicle transporter in the Vertical Integration Building (VIB). The VIB contains two cells for assembly and checkout and two cells capable of storing Titan core vehicles. Technicians connect and test the electrical umbilicals and staging connectors, check out the inertial guidance system, and install connections for the payload.

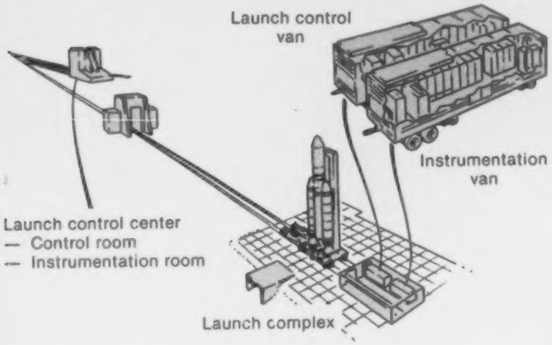
Launch Vehicle Assembly

The core vehicle, mounted on its transporter, is towed to the Solid Motor Assembly Building, where the solid rocket motors and other launcher components are positioned and attached. In the SMAB, technicians thoroughly check all subsystems of the core vehicle and the solid rocket boosters—electrical, propulsion, flight control, hydraulic, guidance, airborne instrumentation, tracking, and flight safety subsystems (fig. 3-10).

Payload Integration and Processing

Payload integration begins months before the payload or launch vehicle arrives at the launch facility, often while the payload is in production.

Figure 3-10.—Titan 34D Checkout and Launch Control Equipment



SOURCE: Martin Marietta.

Payload managers discuss flight plan and payload requirements for vehicle services with the launch vehicle managers and determine the appropriate launch vehicle configuration. Several different payload fairings and upper stages are available, depending on the size, weight, and configuration of the payload.

When the payload arrives at the launch facility, it is assembled, checked out, and tested in facilities off the pad; it is installed on the vehicle at the launch complex several weeks before launch. Payload technicians make all electrical and other connections and test for mechanical and electrical integrity with the launch vehicle.

Launch Complex

The launch complexes 40 or 41,[7] several thousand feet from the VIB, comprise many subsystems (fig. 3-11). Before the vehicle reaches the launch complex, contractor technicians also inspect, test, and repair each subsystem in the appropriate launch complex—the concrete deck of the pad and its exhaust duct, water deluge system (to cool the exhaust and lower the pressure from hot exhaust gases), and vehicle air-conditioning system. They fill the fuel and oxidizer storage tanks and erect support stands for the flexible hoses necessary for filling, venting, and draining the rocket.

After the launcher is completely assembled in the Solid Motor Assembly Building, the transporter tows it to one of the two launch complexes. The Mobile Service Tower rolls into position around the vehicle, and access platforms are lowered into place. Payload specialists then install and test the payload, which has been processed in parallel with the vehicle. Launch vehicle specialists also carry out tests of the vehicle.

The actual time the vehicle must spend on the launch pad depends directly on the type and complexity of the upper stages and payload. With a standard payload, such as a geosynchronous communications satellite, which is encapsulated off-pad, average total pad time is about 6 weeks. If significant checkout and servicing must occur just before launch, as in the case of a payload requiring extensive fueling or the Interim Upper Stage, the payload may remain on the pad for as long as 11 weeks.

In preparation for the final countdown, all the ordnance is installed, and the liquid oxidizer and fuel are loaded into the core vehicle. After batteries of tests, simulations, and verifications, the rocket is declared ready for launch. The range contractor monitors and evaluates all pre-launch environmental conditions at the launch site, including ground winds, gusts, high-altitude winds, ceiling, cloud cover, and visibility.

A typical terminal launch countdown lasts less than one shift, and includes preparations and rollback of the mobile service tower. Command-destruct loops are checked with range safety; the telemetry system is checked. The mobile service tower is rolled back. The core vehicle propellant tanks are pressurized to flight pressure, the pressures inside the solid-fuel rocket motor casings are verified as stable, and the guidance system checked. Final checkout, countdown, and launch are monitored and controlled from the control center, located in the VIB.

Post Launch Activities

Launch processing is not complete with the launch. After liftoff, the launch control center is shut down and reset. The launch area is tested

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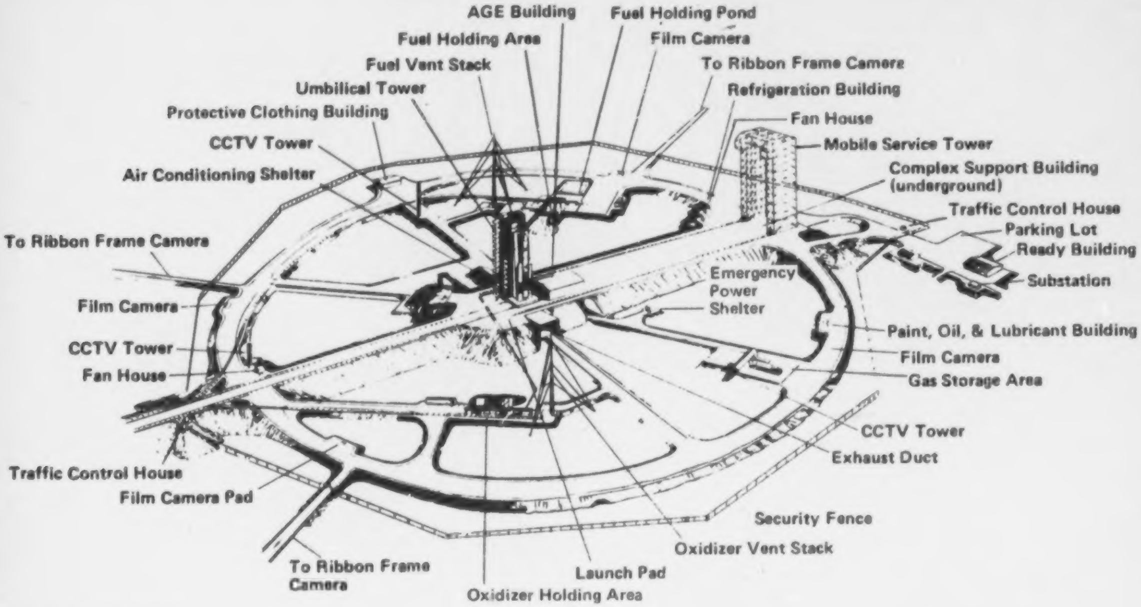
[7] Launch Complex 40 will be used for Titan 34D commercial and government launches. Launch Complex 41 has been modified to accommodate the Titan IV.

Figure 3-11.—Launch Complex 40


AGE Building
Fuel Holding Pond
Fuel Holding Area
Film Camera
Fuel Vent Stack
To Ribbon Frame Camera
Umbilical Tower
Refrigeration Building
Protective Clothing Building
Fan House
CCTV Tower
Mobile Service Tower
Air Conditioning Shelter
Complex Support Building (underground)
Traffic Control House
Parking Lot
To Ribbon Frame Camera
Ready Building
Substation
Emergency Power Shelter
Film Camera
Paint, Oil, & Lubricant Building
CCTV Tower
Film Camera
Fan House
Gas Storage Area
CCTV Tower
Exhaust Duct
Traffic Control House
Film Camera Pad
Security Fence
Oxidizer Vent Stack
To Ribbon Frame Camera
Launch Pad
Oxidizer Holding Area

SOURCE: Martin Marietta.

for toxic vapors and inspected to determine how much damage was sustained from the high-temperature rocket exhaust and vibration, and how much refurbishment the transporter and pad will need before the next launch.

Whether the launch is successful or not, launch data, both from the ground facilities and from the launcher[8] are recorded and analyzed for anomalies or other indications of future problems. If the launch is unsuccessful for some reason, these data may be the only means of determining the cause of failure.

Launch Operations—Vandenberg Air Force Base

As noted, vehicle assembly and processing differ significantly at Vandenberg Air Force Base, primarily because the vehicle is fully assembled on the pad. The launch complex is therefore considerably simpler, as there is no Vehicle Integration Building, Launcher Transporter, or Solid Motor Assembly Building. Consequently the launch rate is lower, as an average of 163 days are required for assembly and launch of each Titan 34D with its payload. This allows only about two and one-quarter launches per pad per year from Vandenberg.

THE SPACE SHUTTLE

Unlike the Titan, the Shuttle orbiter was designed to be reused, which means that launch processing includes recovering and refurbishing the orbiter and the solid rocket boosters (fig. 3-12). The current Shuttle (fig. 3-13; box 3-B) can lift up to 48,000 pounds into low-Earth orbit (about 160 nautical miles above Earth's surface).

Shuttle launch operations requires the use of a wide variety of both advanced and routine tech-

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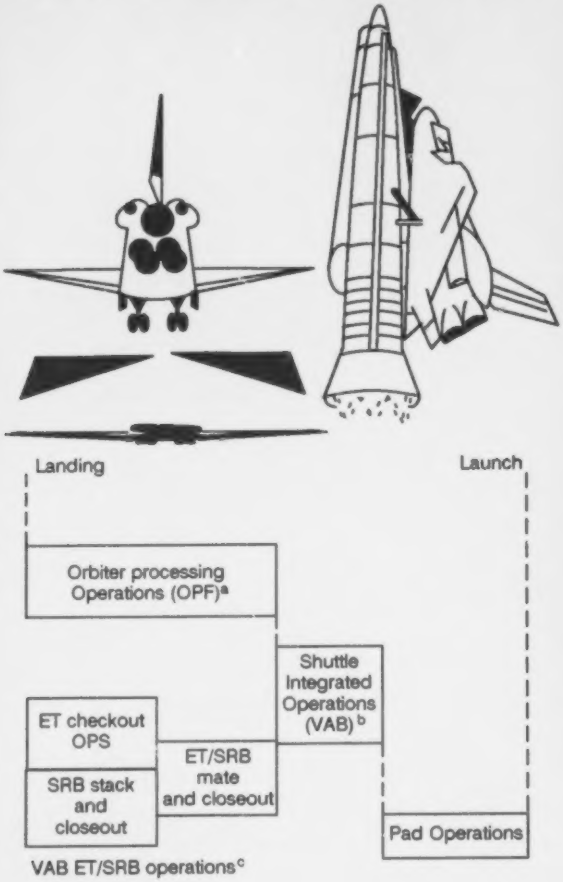
[8] The launch vehicle carries hundreds of sensors to record various environmental factors during launch, including temperature, vehicle acceleration, and vibration. This information is telemetered to the launch complex for later analysis.

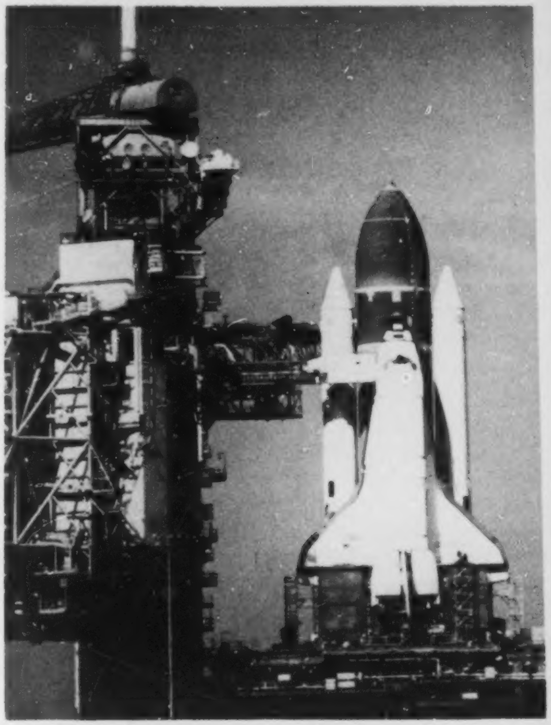
Figure 3-12.—Orbiter Ground Turnaround Operations



[a] Orbiter Processing Facility
[b] Vehicle Assembly Building
[c] Vehicle Assembly Building External Tank/Solid Rocket Booster Operations

SOURCE: National Aeronautics and Space Administration

Figure 3-13.—The Orbiter Challenger Rests on the Mobile Launcher at Pad 39A With the Rotating Service Structure Containing the Payload Canister Moved Back From the Shuttle (January 1983)



SOURCE: National Aeronautics and Space Administration.

nologies and interrelated subsystems. At Kennedy Space Center (KSC), Shuttle processing is carried out by contractors monitored by NASA employees. Lockheed Space Operations Company currently holds the prime contract for this work. Lockheed subcontracts with a variety of other companies, including Rockwell International, the prime contractor for the Shuttle orbiter. Approximately 6,550 contractors and 640 NASA employees directly support Shuttle launch operations at KSC. Johnson Space Center has responsibility for on-orbit mission operations and some launch operations, which involve about 5,675 contractors and 1,065 NASA employees. Marshall Space Flight Center contributes engineering expertise for Shuttle modifications and supports the Shuttle with approximately 1,000 NASA employees and 11,000 prime contractor employees.

Payload Processing

Payloads for the Space Shuttle can be installed either horizontally or vertically (figs. 3-14 and 3-15). Horizontal payloads, such as Spacelab, are installed in the orbiter when it is still in the Orbiter Processing Facility, prior to being mated with the external tank and solid-fuel rocket boosters. Vertical payloads are installed in the orbiter's payload bay after the fully assembled Shuttle arrives at the launch pad.

The payload owner assembles the payload to its final launch configuration by, for example, in-

Box 3-B.—The Space Shuttle Launch System

The shuttle launch vehicle consists of three major subsystems:

- *the orbiter,* with the crew compartment and payload bay, which also contains the three Space Shuttle main engines (SSMEs). About the size of a DC-9, the orbiter weighs about 215,000 lbs., without its payload, and has a 15 by 60 foot cylindrical payload bay.[1]
- *the external tank,* which holds liquid hydrogen and oxygen to fuel the SSMEs.
- *two segmented solid-fuel rocket boosters* (SRBs). These are each made up of 5 motor segments.

At launch, the main engines are ignited, followed seven seconds later by the SRBs. Two and one-half minutes into the flight, explosive bolts separate the orbiter from the SRBs, which parachute into the Atlantic Ocean and are recovered. After about eight minutes of flight, the Shuttle main engines shut down and the external tank separates from the orbiter, breaks up as it reenters the atmosphere and falls into the Indian Ocean. In space, the orbiter maneuvering system, fueled by hypergolic propellants, propells the craft into the orbit desired for the mission.

After the Shuttle crew completes its mission, the orbiter returns to earth where it can land on any of several runways,[2] and is carried back to Kennedy Space Center, to be refurbished for the next launch. Although the Air Force built a Shuttle processing center and launch pad at Vandenberg Air Force Base, CA, it is now in the process of being mothballed.

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[1] Following the loss of Challenger, the fleet now consists of three orbiters—Columbia, Discovery, and Atlantis. NASA has contracted with Rockwell International to build a fourth orbiter, which will replace Challenger by 1992.

[2] For safety reasons, especially after the loss of Challenger, the Shuttle will normally land at Edwards Air Force Base. However, in an emergency, the Shuttle can touch down at Cape Kennedy, or one of the alternative emergency landing sites.

stalling solar panels, antennas or other items, and performing minor repairs. Payload owners have five options for processing payloads, ranging from minimum KSC involvement—essentially "ship and shoot," where the payload is ready for launch and can be installed in the orbiter 2 to 50 days before launch with no servicing, to maximum KSC involvement—where all flight experiments and component hardware must be delivered up to a year before launch for technicians to assemble, integrate and test.[9]

Pre-launch Processing

The basic processing flow is organized according to the integrate—transfer—launch (ITL) concept, which separates the major processing elements and allows certain functions to proceed in parallel until the vehicle is assembled in the Vehicle Assembly Building and carried to the launch pad (fig. 3-16).

Orbiter Processing

Orbiter processing constitutes the critical limit to the achievable flight rate. Refurbishing the orbiter Columbia for the second Shuttle flight consumed nearly 200 work days (three shifts per day). By the ill-fated flight of the Challenger in January 1986, this turnaround time had been reduced to 55 days (fig. 3-17).[10] However, the numerous modifications to the process of orbiter refurbishment, made as a result of the Challenger accident, have led to an estimated future orbiter turnaround of about 160 days, to decrease over four years to 75 days.[11] For a four orbiter fleet, a 75 day orbiter turnaround time would allow 12 to 14 flights per year.

In the Orbiter Processing Facility, NASA contractors check and refurbish every major system in the orbiter after each flight, including the avionics, brakes, electrical systems, and windows. They inspect the Shuttle main engines, and completely replace the bearings and turbines. Any of the 31,000 ceramic tiles of the thermal protection system that are missing or damaged during the flight are also replaced; all tiles are re-waterproofed. Modifications to the orbiters are made during refurbishment.[12] Finally, any horizontal

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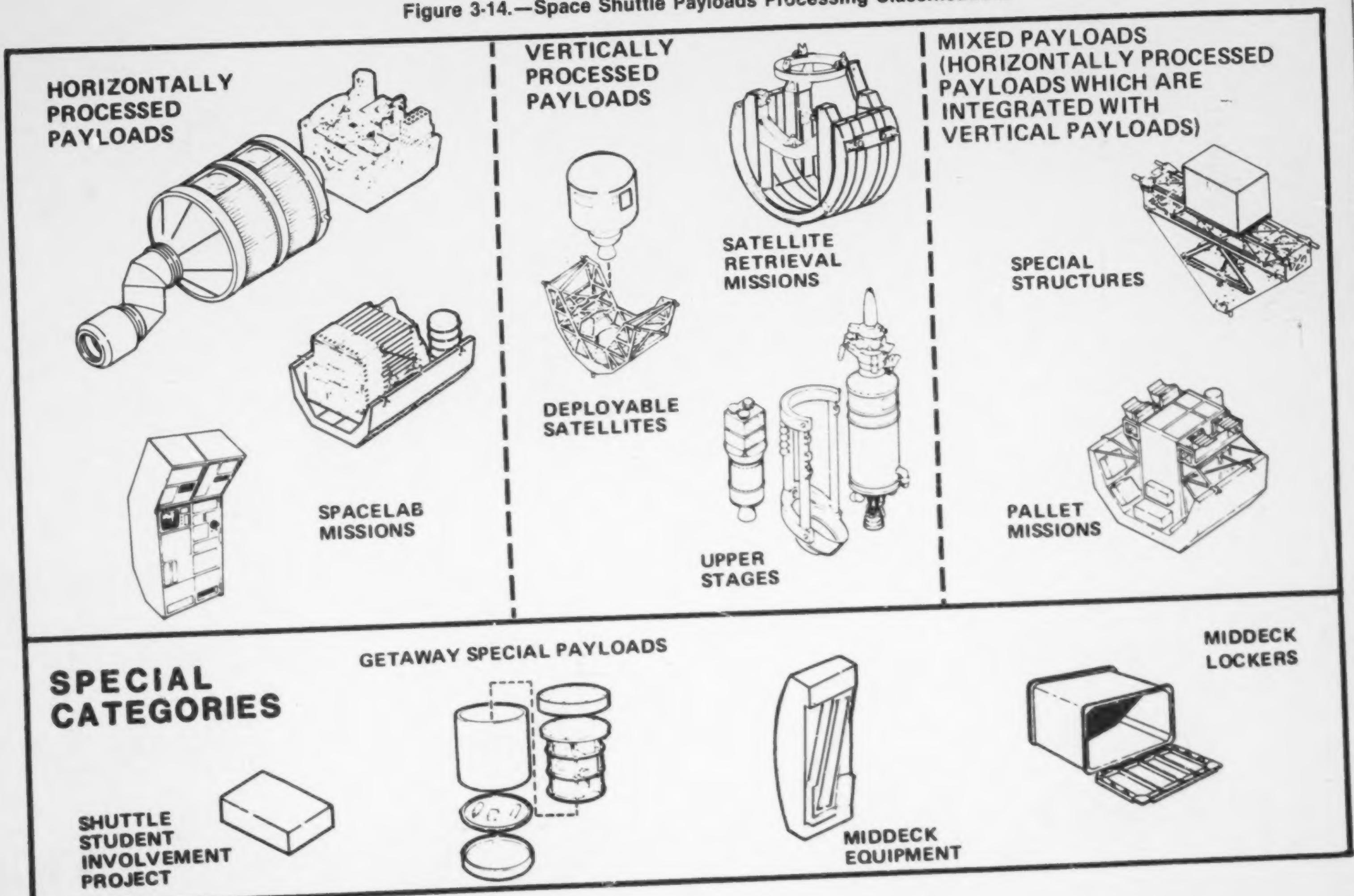
[9] For a detailed breakdown of these options, see James M. Ragusa, "Historical Data and Analysis for the First Five Years of KSC STS Payload Processing," NASA, September 1986, ch. 4.

[10] Charles R. Gunn, "Space Shuttle Operations Experience," paper IAF-87-216, delivered at the 38th Congress of the International Astronautical Federation, Oct. 10-17, 1987.

[11] However, some Shuttle operations experts have raised concerns that new safety related requirements for orbiter processing may make it extremely difficult to reach the goal of 75 days turnaround within 4 years.

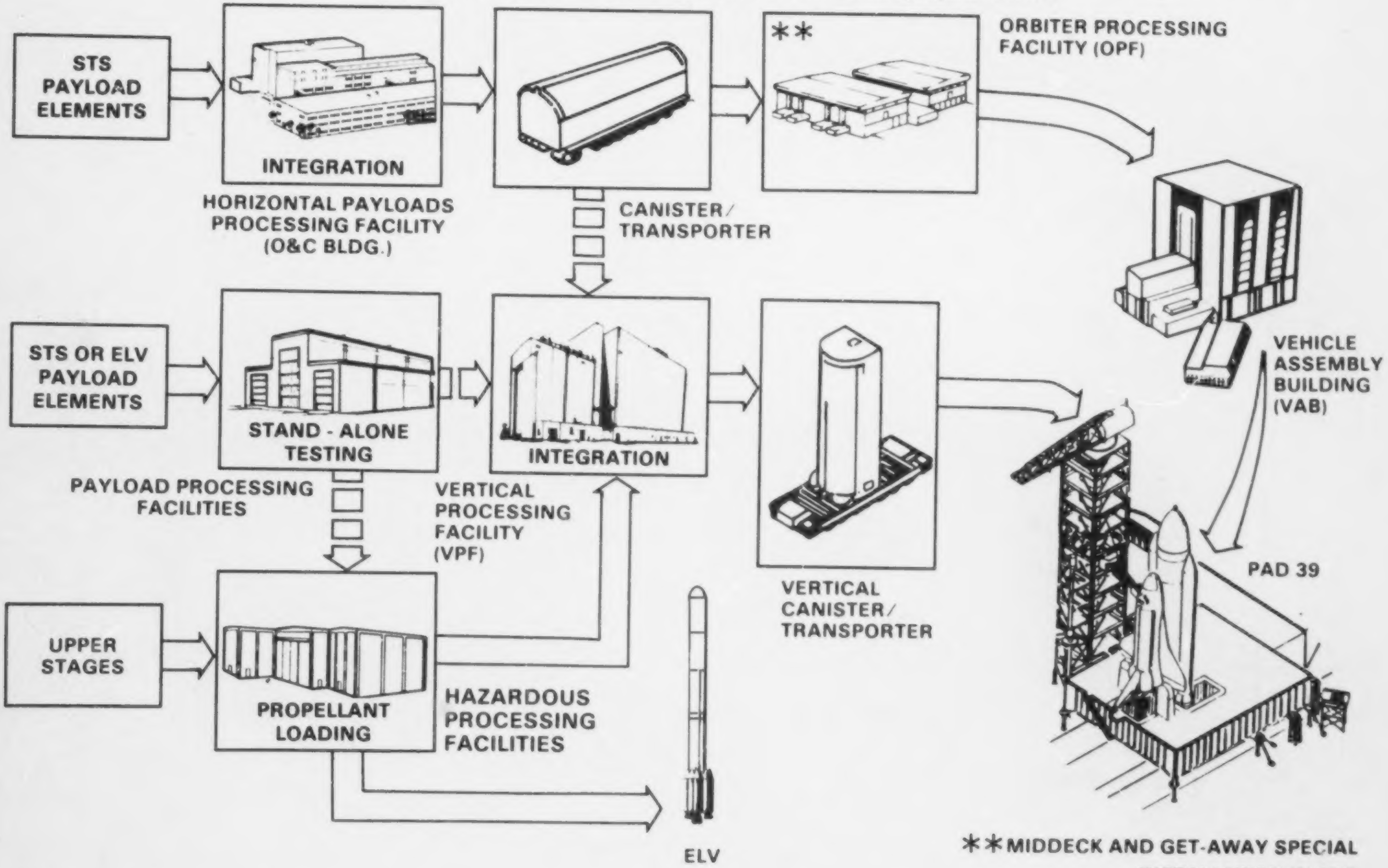
[12] These modifications can significantly lengthen the time necessary to process the orbiter.

Figure 3-14.—Space Shuttle Payloads Processing Classifications


HORIZONTALLY PROCESSED PAYLOADS
SPACELAB MISSIONS
VERTICALLY PROCESSED PAYLOADS
DEPLOYABLE SATELLITES
SATELLITE RETRIEVAL MISSIONS
UPPER STAGES
MIXED PAYLOADS (HORIZONTALLY PROCESSED PAYLOADS WHICH ARE INTEGRATED WITH VERTICAL PAYLOADS)
SPECIAL STRUCTURES
PALLET MISSIONS
SPECIAL CATEGORIES
SHUTTLE STUDENT INVOLVEMENT PROJECT
GETAWAY SPECIAL PAYLOADS
MIDDECK EQUIPMENT
MIDDECK LOCKERS

SOURCE: National Aeronautics and Space Administration.

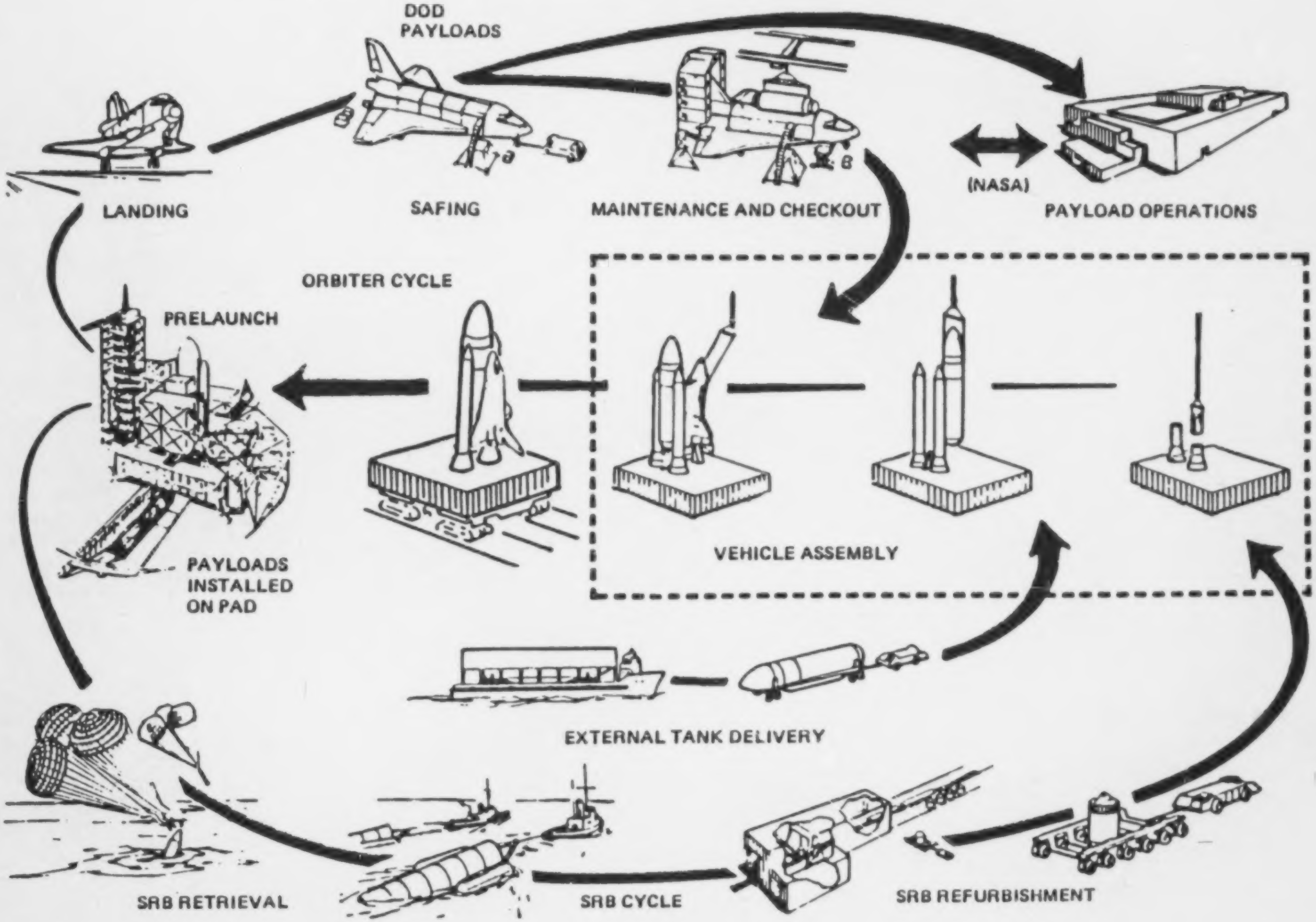
Figure 3-15.—Payload Processing Flows at the Kennedy Space Center


STS PAYLOAD ELEMENTS
INTEGRATION
HORIZONTAL PAYLOADS PROCESSING FACILITY (O&C BLDG.)
**
ORBITER PROCESSING FACILITY (OPF)
CANISTER/ TRANSPORTER
STS OR ELV PAYLOAD ELEMENTS
STAND - ALONE TESTING
PAYLOAD PROCESSING FACILITIES
INTEGRATION
VERTICAL PROCESSING FACILITY (VPF)
VEHICLE ASSEMBLY BUILDING (VAB)
VERTICAL CANISTER/ TRANSPORTER
PAD 39
UPPER STAGES
PROPELLANT LOADING
HAZARDOUS PROCESSING FACILITIES
ELV

**MIDDECK AND GET-AWAY SPECIAL INSTALLATION IN OPF

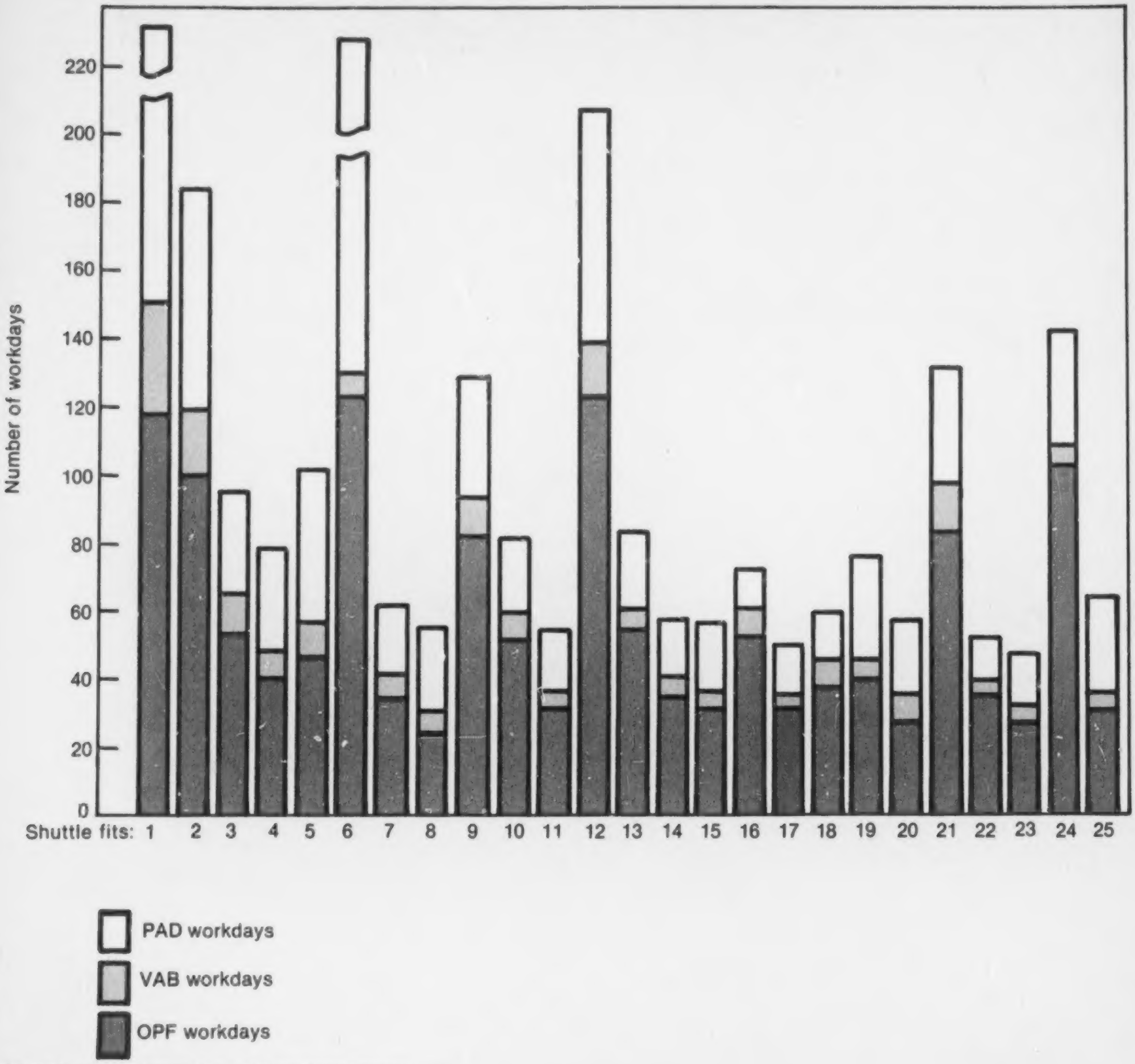
SOURCE: National Aeronautics and Space Administration.

Figure 3-16.—Kennedy Space Center Space Shuttle System Ground Flow


DOD
PAYLOADS
LANDING
SAFING
MAINTENANCE AND CHECKOUT
(NASA)
PAYLOAD OPERATIONS
ORBITER CYCLE
PRELAUNCH
PAYLOADS
INSTALLED
ON PAD
VEHICLE ASSEMBLY
EXTERNAL TANK DELIVERY
SRB RETRIEVAL
SRB CYCLE
SRB REFURBISHMENT

SOURCE: National Aeronautics and Space Administration.

Figure 3-17.—Orbiter Ground Turnaround Experience



SOURCE: National Aeronautics and Space Administration.

payloads, such as Spacelab, are installed in the payload bay.

Solid Rocket Boosters (SRBs)

The contractor (Morton Thiokol) ships new solid-fuel rocket motor segments and associated hardware, including the forward and aft closures, nozzle assemblies, and nozzle extensions by rail. When the segments arrive at KSC, they are moved into the Rotational Processing and Surge Facility where they are inspected and stored until needed.

Assembling and testing the SRBs requires about 33 days (three shifts). After the aft booster assemblies are attached to support posts on the mobile launcher platform, the rocket motor segments—all filled with live propellant—are added, inspected and tested. During the stacking process, which lasts several hours per segment, everyone but the stacking crew must evacuate the Vehicle Assembly Building (fig. 3-18).

External Tank

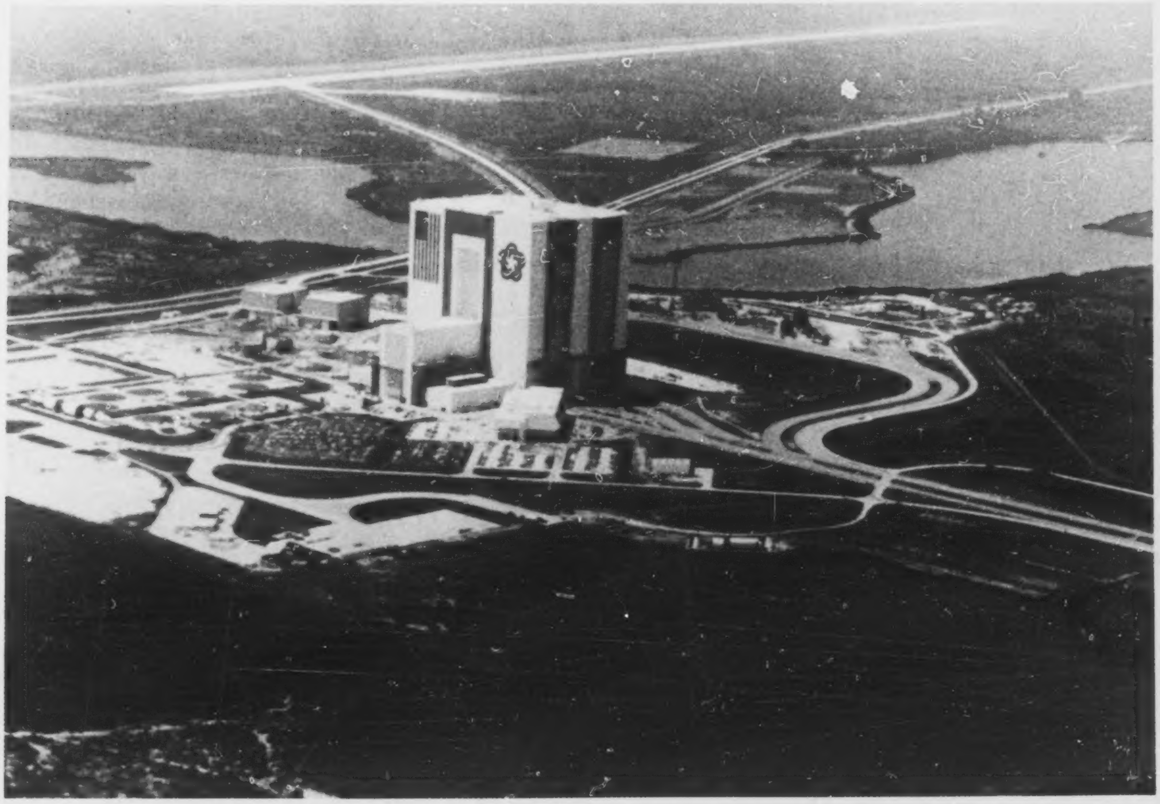
Meanwhile, the external tank, which is manufactured by Martin Marietta, is transported to KSC by sea barge from the Michoud Assembly Facility at New Orleans, Louisiana. In the Vehicle Assembly Building (VAB), contractors inspect the external insulation and connections for ground support equipment, as well as the cryogenic tanks for holding liquid oxygen and liquid hydrogen. A crane hoists the tank to a vertical position and transfers it to the mobile launcher platform, where it is mated with the twin SRBs. The electrical systems are checked and the many fluid valves tested.

Vehicle Assembly and Integration

After orbiter processing is complete, it is towed to the VAB High Bay, lifted to the vertical, and mated to the external tank and SRBs (fig. 3-19). After mating all the sections of the Shuttle and connecting all umbilicals, technicians test each connection electrically and mechanically.

The computer-controlled launch processing system, which is operated from the firing rooms of

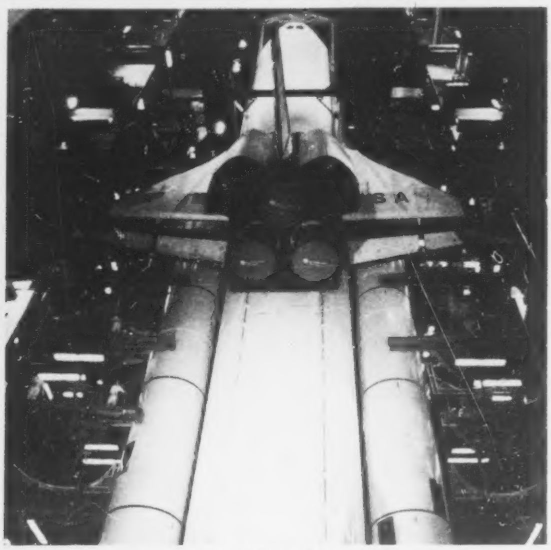
Figure 3-18.—Aerial Photograph—Important Facilities at Kennedy Space Center



Dominating the view is the Vehicle Assembly Building, which is 525 ft. high. The low structure in the foreground is the Launch Control Center.

SOURCE: National Aeronautics and Space Administration.

Figure 3-19.—The Orbiter Columbia, Undergoing Launch Processing for Its Second Voyage Into Space, Is Gently Lowered Toward the Solid Rocket Boosters and External Tank for Mating (August 1981)



SOURCE: National Aeronautics and Space Administration.

the launch control center, semi-automatically controls and checks out much of the Shuttle vehicle, both in the VAB and at Launch Complex 39. If any subsystem is found unsatisfactory, the computer will provide data that help isolate the fault.

Transfer and Launch

When the Shuttle is fully assembled on the Mobile Launch Platform, a crawler-transporter slips under and slowly (1 mph) moves the Shuttle to Launch Complex 39A or B (fig. 3-20). Once at the pad, workers gain access to the Shuttle through the fixed service structure, which also provides liquid hydrogen and oxygen to the external tank. The rotating service structure gives access to service fuel cells and the life-support system, to load and remove payloads, and to load hypergolic fuels for the orbital maneuvering system and the reaction control system. Those payloads to be installed vertically are transported to the rotating service structure in a protective payload canister.

After the Shuttle arrives at the pad, most checkout operations are controlled from the launch control center. After these operations, power is applied to the orbiter and supporting ground support equipment, launch-readiness tests are performed, and the tanks are prepared to receive their fuels. The Shuttle is now ready for the cryogenic propellants to be loaded and the flight crew to board.

During the final six or seven hours of the countdown, the mission software is updated and the liquid hydrogen and liquid oxygen loaded into the external tank. Finally, the flight crew and operations personnel complete all preparations and the Shuttle lifts into space (fig. 3-21).

Mission Operations

Mission operations (table 3-1) comprise all activities associated with planning and executing a mission and the payloads to be carried. The primary focus is on gathering data, performing analyses, and developing the software required to meet the mission's objectives. Mission operations begin the first day a payload is conceived, continue through the day of the launch, and end only after the mission is satisfactorily completed and the data analyzed. From early mission planning to completion, mission operations for a Shuttle flight may take two years or more.

Tracking stations scattered around the world and the Tracking, Data, and Relay Satellite System (TDRSS) give orbiter crews access to Mission Control for most of the orbit.[13] The Johnson Space Center (JSC) at Houston, TX is the central control point for Shuttle missions; payloads and related systems are controlled from the Jet Propulsion Laboratory (Pasadena, CA), the Goddard Space Flight Center (Greenbelt, MD), or JSC.

Post-launch Processing

Two minutes into the Shuttle's flight, the two solid-fuel rocket boosters are jettisoned and parachute into the Atlantic Ocean downrange from KSC. Two specially designed retrieval vessels recover the boosters and their various components. The smaller components are hauled on board the ships, whereas the boosters are towed back to the

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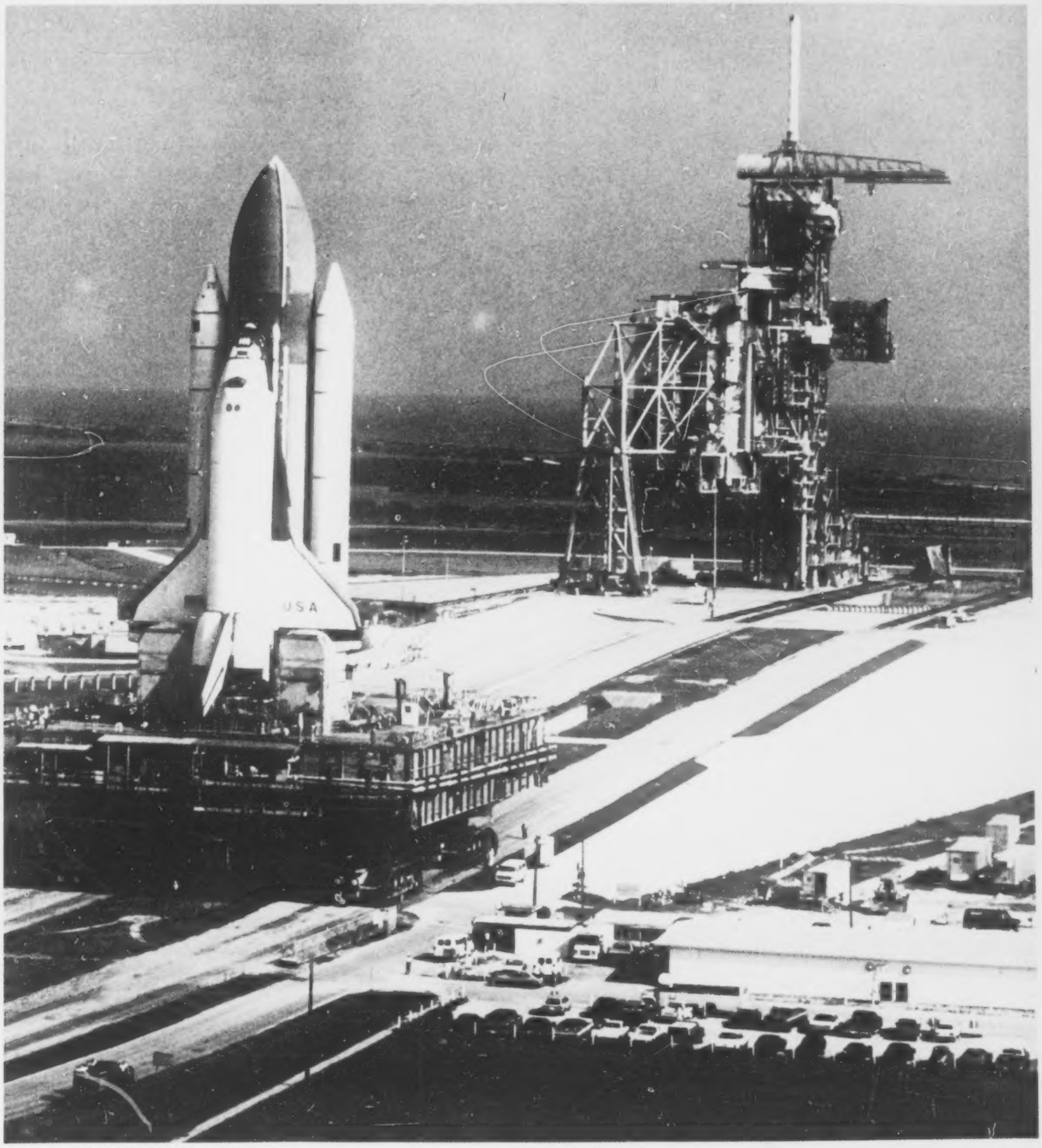
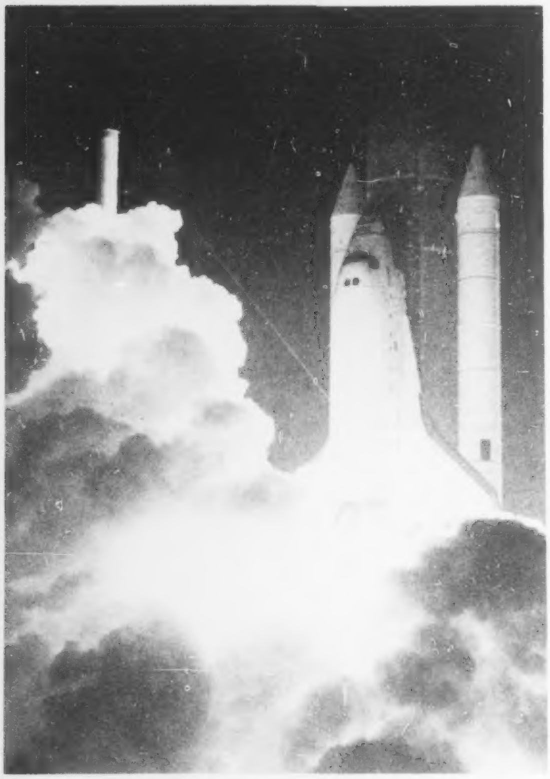
[13] When TDRSS deployment is complete (three spacecraft), it will allow the crew to contact Mission Control nearly 100 percent of the time in orbit. The second of two TDRSS satellites is scheduled for deployment on the first Shuttle flight after standdown.

Figure 3-20.—The Space Shuttle Columbia Begins Its Roll Up the Ramp to Pad 39A After Completing the 3½ Mile Journey From the Vehicle Assembly Building (September 1982)



SOURCE: National Aeronautics and Space Administration.

Figure 3-21.—The Space Shuttle Challenger Lifts Off in the First Nighttime Launch of the Shuttle Era (August 1983)



SOURCE: National Aeronautics and Space Administration.

Table 3-1.—Shuttle Mission Operations Functions

- Design Shuttle trajectory and flight plan
- Develop flight and ground documentation to support operations
- Provide mission support with flight planning, flight systems, payload support, and trajectory teams
- Provide maintenance, operations, mission reconfiguration, and sustaining engineering for support facilities (mission control center and simulation and training facilities)
- Develop plans and provide training to crews, customers, and flight controllers
- Develop operating concepts and requirements

SOURCE: Johnson Space Center.

KSC Solid Rocket Booster Disassembly Facility. At this facility, the boosters and other components are washed, disassembled, cleaned, and stripped before they are shipped by rail to the prime contractor (Morton Thiokol) for refurbishing and reloading.

When the Shuttle orbiter returns from its mission in space, it normally lands at Edwards Air Force Base in California. In emergencies, it can also land at KSC; White Sands, NM; Zarogosa, Spain; Casablanca, Morocco; Rota, Spain; or Guam. After landing, it must be drained of hazardous fuels and inspected for any exterior damage. Payload technicians remove any payloads brought back to Earth. If it lands anywhere but KSC, the orbiter must be lifted onto the back of a specially equipped Boeing 747 and flown back to the Shuttle Landing Facility at KSC.

Chapter 4

Technologies and Management Strategies

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Chapter 4

Technologies and Management Strategies

INTRODUCTION

Launch and mission operations could be made more efficient and less expensive by employing emerging technologies in the three major components of the launch system—ground support facilities, mission control facilities, and launch vehicles. These technologies must be put to work in an institutional structure and culture that facilitates, rather than hinders, their use. Therefore, efficient management strategies must also receive consideration.

The first section of this chapter, *Technologies for Ground and Mission Operations*, introduces operations technologies that could be used in an advanced launch system specifically designed for low cost. They are consonant with technologies for the Advanced Launch System (ALS) currently under consideration by the Air Force and NASA. Many of them would also be appropriate either for enhancing existing launch systems or for inclusion in new launch systems built with existing technologies.

The next section, *Technologies for Launch Vehicles*, introduces launch design principles and explores technologies that could be inserted into vehicles to reduce the costs of launch and mission operations. The section on *Management Strategies* examines some methods of organizing and managing launch systems to achieve low cost operations. Finally, *Assessing Technological Options and Costs* discusses the principal trade-offs to consider in designing new facilities and a new launch operations strategy, and explores how these concepts and techniques may affect the design, costs, and processing of vehicles and payloads.

TECHNOLOGIES FOR GROUND AND MISSION OPERATIONS

Because of considerable overlap in the technologies that could be employed in launch and mission operations, this section discusses them together. Some of these technologies exist in one form or another today, but would need to be modified for specific space applications; others require additional research and development. Table 4-1 lists some major categories of technologies or applications. Those marked with an asterisk are described and discussed briefly in the text.

Table 4-1.—Technologies for Operations

- Automated data management system*
- Automated test & inspection*
- Automated launch vehicle and payload handling
- Database management systems
- Computer-aided software development*
- Expert systems*

*Discussed in text.

SOURCE: Office of Technology Assessment, 1988.

Automated Data Management System

Computer work stations linked through a network that provides a common database can assist the speed and accuracy of information transfer and make it possible to speed up sign-off procedures. Such automated data management systems are in common use in manufacturing and service industries.

"One of the highest cost items, if you look at the Shuttle program today, is the operations cost associated with all the data processing systems involved," observed one OTA workshop participant. On-board systems, flight-design-and-preparation, training, launch processing, and mission control systems have all evolved over the years. They are complex, written in different computer languages, and sometimes poorly documented. Each uses different, unlinked databases. Participants further explained that individual program elements have their own autonomous mission planning jobs and their own manner of sending information among the subsystems; people use "bulky paper, communications, phone calls," and group meetings, and use no integrated approach to transferring the data to all elements, even though they are all interdependent. As a result, although the flow of information within NASA during the launch sequence is excellent, during the months leading up to launch, information flow is very poor. The events before the failure of the Challenger provide an unfortunate example of how constrained the flow of information can be in the months prior to launch.[1]

An automated data management system should be incorporated into any future launch systems. Workshop participants urged planners of future systems to: standardize the architecture of onboard and ground systems, standardize the code used, and minimize custom hardware and software by using commercially available products where possible. One participant estimated that an integrated paperless information-management system could reduce the time spent in launch operations by one-half. The space station project plans an integrated, paperless information system to assist in managing space station operations. Many of the lessons learned in that effort could be applied to launch and mission operations.

Automated Test and Inspection

Automating certain test and inspection procedures could also reduce costs. However, before automating current procedures, they should be carefully examined to see which ones are necessary, and whether some steps can be simplified or even eliminated. "It makes no sense to automate nonsense," asserted one workshop participant. Certain kinds of automation such as the assembly and test of electrical and electronics systems may be technically straightforward, but difficult to incorporate because workers understand current procedures well and are reluctant to change. Workers require incentives and additional training to smooth the transition to new procedures.

Automating the assembly and test of mechanical, pneumatic, and fluid systems is a major challenge. Today, mechanical and fluid systems create the most operations delays and verification problems, whereas electrical and electronic systems are already well-instrumented and tend to be reliable. For example, on the Delta launch vehicle, more time is spent in mating the strap-on solid- fuel rocket motors to the liquid rocket, fitting the cork insulation, and doing the leak check on the pneumatic hydraulic systems than in checking out the entire electronic system. On the Atlas, part of the leak check test calls for looking for bubbles or listening for leaks—something very difficult to automate.

Box 4-A presents an example of a semi-automated system for inspecting the thermal protection tiles on the Shuttle orbiter. The system, developed by NASA, Stanford University, and Lockheed Space Operations Company, promises to make tile inspection more reliable and may lower its cost.

Computer-Aided Software Development

Traditional methods of developing software and writing the necessary computer code are highly labor-intensive and require skilled programmers. However, new techniques promise to improve the speed and accuracy of software development.

Computer-aided software development options range in power and complexity from commercially-available, so-called software engineering environments,[2] which are program libraries, editors, and program debuggers, to automatic programming.[3]

The benefits of using computer-aided software development include reliability, economy, and responsiveness, a key aspect of operational flexibility. Proponents of computer-aided software development suggest that it will be applicable to both mission control and ground operations.

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[1] *Report of the Presidential Commission on the Space Shuttle Challenger Accident* (Washington, DC: U.S. Government Printing Office, 1986), ch. 5.

[2] For example, SmallTalk: Adele Goldberg, *Smalltalk-80* (Reading, MA: Addison-Wesley, 1983).

[3] Skeptics contend that "automatic programming has always been a euphemism for programming with a higher-level language than was presently available to the programmer."—D.L. Parnas, "Software Aspects of Strategic Defense Systems," *American Scientist*, November 1985.

Box 4-A.—Shuttle Tile Automation System

Inspecting the some 31,000 thermal protection system (TPS) tiles on the Shuttle orbiters and repairing damaged ones is highly labor intensive. Automating the inspection procedures could reduce overall labor costs, and increase inspection speed and accuracy. In 1986 NASA began the Space Systems Integration and Operations Research Applications (SIORA) Program as a cooperative applications research venture among NASA-KSC, Stanford University, and Lockheed Space Operations Company. One of its initial tasks is to apply automation and robotics technology to all aspects of the Shuttle tile processing and inspection system.

The team is developing an automated work authorization document system (AWADS) that will enable technicians to document the condition of each tile, determine any necessary repairs or replacement, and generate work instructions. With the automated system, the computer, which is programmed to recognize each technician's voice, prompts the technician to find the correct tile, enter its number, and report on its condition in a systematic way. The TPS quality control technician first inspects the tiles after each flight and enters the part number, location, and condition of each tile into a computer base by voice. The computer's central database automatically generates a problem report in electronic format, which a TPS engineer uses to identify and recommend proper repair procedures for the tile. The problem report proceeds through an electronic signature loop until final approval for the repair. Finally, the TPS technician uses the voice data entry method to indicate tile status as repair procedures are completed.

The AWADS system and other automated systems developed in the SIORA program use the Ada programing language,[1] the software environment that will be used in the space station, and other large NASA programs in the future. It offers the advantages of excellent portability from one hardware system to another, a rich set of programming functions and tools, and a uniform code documentation. The tile automation system is expected to be operational by January 1989.

[1] Ada was originally developed for use by the armed services. It has become the DoD software standard.

When used in the appropriate application, "it will minimize programming time and effort . . . and improve the probability of mission success."[4]

Expert Systems

Some systems attempt to capture experts' problem-solving knowledge in a computer program. So-called "expert systems" could provide considerable assistance in automating complex launch and mission operations procedures, such as fuel loading and gantry disconnect, where the experts' knowledge can be codified. Expert systems can also be applied to maintenance checks and fault isolation procedures which are currently performed manually. In their most mature form, expert systems are used as diagnostic assistants. Knowledge engineers and programmers have developed expert systems for a diversity of disciplines, including medicine, geology, chemistry, military science, electronics, education, agriculture, and law.

Expert systems solve problems arising in a particular discipline using the same rules of thumb that humans employ in decisionmaking. A typical expert system has two parts:

- A knowledge base: typically including descriptions of relationships among objects or a set of rules describing actions. These rules take the form, "*if* the power is turned off, *then* the system won't work."
- An inference engine: typically including a rule base (in this case, a set of rules of thumb to be used for problem-solving) and meta-rules (instructions that determine the order in which to use the rules in the rule base when solving a problem).

Each knowledge base is specific to a particular domain of knowledge and must be appropriate for the type of problem to be solved. The inference engine, on the other hand, is generic; it is developed by programmers trained in the methods of artificial intelligence and, once developed, can be used with appropriate knowledge bases to solve a variety of problems.[5] At present, knowledge engineers act as intermediaries in the process. The knowledge engineers and programmers are now aided, and may eventually be replaced, by computer programs that help translate the experts' rules of thumb into formats the inference engine can interpret.[6] Box 4-B discusses three expert systems that could be used for launch operations.

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[4] USAF Space Division, *Launch Systems for the Strategic Defense Initiative—Data Book* (Los Angeles Air Force Station, CA: Headquarters, U.S. Air Force Systems Command Space Division, December 1986), p. 6-93.

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[5] Cf. critiques by F.P. Brooks, Jr., "No silver bullet—essence and accidents of software engineering," *Computer*, April 1987, pp. 10-19; and F. Flores and T. Winograd, *Understanding Computers and Cognition: A New Foundation for Design* (Norwood, NJ: Ablex, 1986).

[6] W.B. Gevarter, "The nature and evaluation of commercial expert system building tools," *Computer*, May 1987, pp. 24-41.

Box 4-B.—Expert Systems for Launch Operations

Expert systems that are potentially useful in space transportation systems include **LES** (LOX Expert System), **KATE** (Knowledge-Based Automatic Test Equipment), and **ISIS** (Intelligent Scheduler and Information Systems).[1]

LES is a quasi-expert system built to demonstrate monitoring and troubleshooting of the portion of the Shuttle Launch Processing System that performs liquid oxygen (LOX) loading of the Shuttle at KSC.[2] Sensors at numerous points in the LOX loading system report the temperature, pressure, and operating status of various subsystems to the Shuttle Launch Processing System. LES was designed to:

1. identify abnormal sensor readings immediately;
2. deduce whether an abnormal reading indicates a problem in the loading procedure or merely failed instrumentation; and
3. override reactions to apparent system failures, such as the safing operation, countdown hold, or launch abort, if it identifies failed instrumentation as the cause.

LES produces reports in the format of an Interim Problem Report, a paper form used at KSC for many years (figure 4-1). LES can also display and print schematic diagrams of the wiring and plumbing it monitors.

In developing prototype expert systems for use in launch operations, NASA engineers chose to apply an expert system to the LOX loading system because a complete functional description of the Shuttle Launch Processing System was available. This improved LES's performance but made LES a questionable model for other expert systems that must reason about domains about which they have only fragmented and sometimes inconsistent descriptions. An upgraded version of LES (KATE—see below) subsequently demonstrated an ability to diagnose problems even when it had only limited information about the domain, by producing a list of "suspect" faults.

LES's developers also chose to use algorithmic reasoning rather than applying "rules of thumb" gained by experience. In other words, LES follows programmed instructions to achieve full logical consistency of its diagnoses. In this respect LES is not a true expert system. It also cannot understand systems with feedback or diagnose multiple failures.

Nevertheless, LES's developers are enthusiastic about its potential for use on other KSC fluids systems. They suggest that "the cost of . . . software would plummet while the reliability and safety of the control software would rise dramatically."[3]

KATE is an expert system developed to demonstrate monitoring, diagnosis, and control of systems with electrical, mechanical, hydraulic, and pneumatic components.[4] The present KATE system is being

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[1] For other examples, see NASA Advanced Technology Advisory Committee, Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, NASA TM-87566, v. II, March 1985, and NASA Ames Research Center, "Systems Autonomy Technology—Program Plan," briefing slides, 1987.

[2] J.R. Jamieson, et al., "A knowledge-based expert system for propellant system monitoring at the Kennedy Space Center," *Proceedings of the 22d Space Congress, Cocoa Beach, Florida*, 1985, pp. 1-9; E.A. Scarl, et al., "A fault detection and isolation method applied to liquid oxygen loading for the Space Shuttle," *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*, 1985, pp. 414-416.

[3] Jamieson, et al., op. cit., pp. 1-9.

[4] E.A. Scarl, et al., "Diagnosis and sensor validation through knowledge of structure and function," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. SMC-17, No. 3, May/June 1987, pp. 360-368; M. Cornell, "Knowledge-Based Automatic Test Equipment," *Proc. ROBEXS* 86, NASA JSC, June 1986.

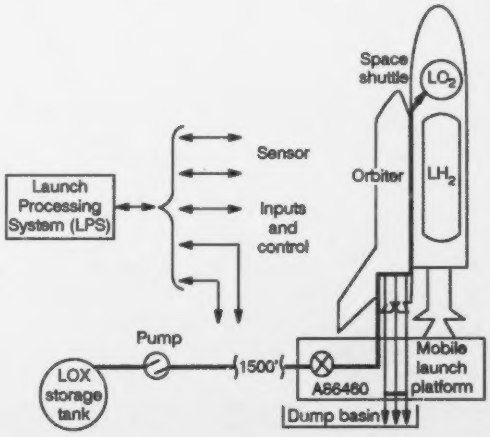
Figure 4-1

```
*************** I N T E R I M   P R O B L E M   R E P O R T ***************
              Monday the twenty-fifth of March, 1985; 3:38:23 pm
                    REPORTED BY: LES the Lox Expert System

PROBLEM DESCRIPTION:
GLOX3043E the replenish valve open measurement ne. 2 is not reading correctly.
It now reads: OFF   ,but should read: ON  .

ANALYSIS & TROUBLESHOOTING STEPS:
1) GLOP2045A the replenish valve signal pressure measurement detects the current
    state of A33706, because if A33706 was failed to ON, then GLOP2045A would
    have to be reading between -0.5 and 0.5.
2) GLOP2045A the replenish valve signal pressure measurement detects the current
    state of A33708, because if A33708 was failed to ON, then GLOP2045A would
    have to be reading between -0.5 and 0.5.
3) GLOP2045A the replenish valve signal pressure measurement detects the current
    state of A33709, because
     if A33709 was failed to ON, then GLOP2045A would have to be reading
     between -0.5 and 0.5.
     however, GLOP2045A is reading 15, thus clearing:
     20-PSI-PR1, A33784, A33709, A33706, K105,  and A33708.
      Suspects now are: A86460, 6401A452, 6602A1-F2, +22D180B,  and GLOX3043E.
4) GLOX2043E  the replenish valve open measurement no. 1 is NOT reading
    correctly thus clearing:  GLOX3043E.
      Suspects now are A86460, 6401A452, 6602A1-F2,  and +22D180B.
5) GLOH3044A the replenish valve position indicator no. 2 detects the current
    state of A86460, because if A86460 was between 0.0 and 93, then GLOH3044A
    would have to be reading between -5.0 and 98.
    however, GLOH3044A is reading 99, thus clearing:
    A86460.
      Suspects now are: 6401A452, 6602A1-F2,  and +22D180B.
6) GLOX2035E replenish valve secondary pressures okay measurements detects the
    current state of +22D180B, because if +22D180B was failed to OFF, then
    FLOX2035E would have to be reading OFF.
    however, GLOX2035E is reading ON, thus clearing:
    6602A1-F2 and +22D180B.
     Suspects now are: 6401A452.
Monday the twenty-fifth of March, 1985;
3:38:42 pm
At this point it appears that the most likely
single point failure is 6401A452 the
replenish valve open limit switch. The rest
of the measurements will be searched for
conflicting evidence.
7) The balance of the RELATED MEASUREMENTS
have been examined, and cannot add additional
information to the above analysis.
CONCLUSION:

It is determined that the most likely single
point failure is 6401A452 the replenish valve
open limit switch
Thank you----LES
Monday the twenty-fifth of March, 1985;
3:38:44 pm
```



SOURCE: National Aeronautics and Space Administration.

demonstrated on a laboratory air purge system. Like LES, KATE is neither designed to understand systems with feedback nor to diagnose multiple failures.

KATE was developed from LES by modifying the program so that it could not only diagnosis faults in a monitored system but could also control the system. For example, it can turn valves and motors on and off in an attempt to keep sensor measurements within specified limits. LES diagnoses faults by: 1) hypothesizing faults that might cause sensors to report the undesirable measurements observed; and then 2) deducing whether they would cause the undesirable measurements. KATE's developers realized that the same method could be used to hypothesize commands that might cause sensors to report acceptable measurements and then deducing whether they would cause all sensors to report acceptable measurements.

KATE's developers added an ability to learn about its domain by experimentation. KATE's Learning System enables KATE to construct a partial knowledge base, or a complete knowledge base of a simple system, by observing the performance of a system to which it is connected. KATE "issues combinations of inputs, each time looking for measurement reactions and filing the results in a table. When all combinations have been tried, the table is evaluated to produce frames[5] representing the tested system."[6] KATE has produced complete knowledge bases about simple digital circuits by experimenting with them. KATE's approach may be inappropriate for learning about complicated real systems because experimenting with all combinations of inputs would take time and might even cause failures in some systems.

ISIS[7] is a job scheduler. It is designed to solve "work flow" problems such as:

> We want to produce Tethered Upper Stage Knobs (TUSKs)[8] at the maximum rate possible without buying new tools. Each TUSK requires casting for five hours, milling for two hours, grinding for three hours, two different half-hour inspections, and five different one-hour tests. We have two molds, one milling machine, two grinding machines, one inspector qualified to perform each inspection, and one test cell for each required test. The casting must precede the milling, which must precede the grinding. Any tests and inspections, which are the last stages of TUSK manufacture, can be done in either order, although it has proven economical to inspect before testing. The time required to transfer an unfinished TUSK from one work cell to another depends upon the origin and the destination; these times have been measured and tabulated. By what path or paths should unfinished TUSKs be routed among the operations?

If only one TUSK were to be produced, this scheduling problem would be a "traveling salesman problem" with additional constraints upon the routes the "salesman" [unfinished TUSK] can take through the "cities" [operations] he must visit. The additional constraints can be used to simplify the search for the shortest route, but the resulting simplified problem is still of the traveling-salesman type. The computational effort required to solve such problems by the fastest published methods[9] grows exponentially (in the worst case) as the number of operations increases. The scheduling problem in the example above, although far simpler than an actual one, is even more complicated than a traveling salesman problem; it is analogous to the problem of coordinating the itineraries of a succession of traveling salesmen—one departing each day—so that the average trip duration is minimized, subject to the condition that no two can be in the same city on the same day.

At KSC, Shuttle processing operations are now scheduled manually by individuals who maintain charts showing durations of individual operations as horizontal bars; these Gantt charts cover several walls. Portions of the charts are photographed, printed, and distributed daily and weekly. When schedule interruptions, delays, or speed-ups occur, schedulers modify the charts; they must determine a new schedule which satisfies all constraints, for example, on the order in which operations can be performed. Except fortuitously, such a procedure will not result in the most efficient schedule for the workforce. Although schedulers also try to minimize processing time, they find it impossible to determine and compare all possible schedules satisfying all constraints resulting in the most efficient schedule.[10] How much vehicle processing time could be reduced and costs saved by more efficient computer scheduling has not been explored.

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[5] A "frame" is a list of statements about an object's properties and relations (e.g., connections) to other objects.

[6] M. Cornell, op. cit.

[7] Mark S. Fox and Stephen F. Smith, "ISIS—a knowledge-based system for factory scheduling," *Expert Systems,* vol. 1, No. 1, July 1984, pp. 25-49.

[8] For illustration only. Any resemblance to acronyms in current or previous use is purely coincidental.

[9] S. Kirkpatrick, et al., "Optimization by simulated annealing," *Science,* vol. 220, No. 4598, May 13, 1983, pp. 671-680.

[10] Critical path methods are used to monitor payload integration schedules at KSC but cannot be used to schedule processing operations; these methods can identify the sequence of operations that will take the longest to perform (the "critical path") but cannot rearrange the sequences to save time.

TECHNOLOGIES FOR LAUNCH VEHICLES

Vehicle Design Principles

As experience with the Space Shuttle illustrates, vehicle design significantly affects launch and mission operations and plays a crucial part in the ability to reduce costs. Many Shuttle subsystems are extremely difficult and time consuming to maintain or repair because Shuttle designers focused on attaining optimum performance and high safety, often at the expense of ease of ground operations, maintenance, or mission control.[7] In order to determine which technologies might reduce costs most, launch system designers should consider certain design principles.

Include all segments of the launch operations team (including logistics personnel) in the design of any new launch system.

When planning and designing a new launch system, it is essential to consider the entire system as an interactive entity, including the operations infrastructure, and operations management. This enables system designers to anticipate potential operations and maintenance problems and provide for them before the system is built.

Reduce number and complexity of tasks requiring human intervention.

Complexity of documentation, maintenance, and interfaces among subsystems generally lead to higher system costs. Therefore, reductions in the number and variety of tasks necessary for launch preparation, especially those that require human involvement, could assist in reducing launch costs.[8] However, vehicle subsystems themselves can be complex, if they are designed to simplify each procedural step. For example, including self-testing electronics in an avionic subsystem makes that subsystem complex, but reduces the number of tasks required of launch personnel. ESA achieved simplicity in the Ariane by using a high degree of commonality in the design of different vehicle stages, and evolutionary design from one vehicle to the next. In addition, Arianespace has simplified the payload/launcher interfaces that are required for Ariane.

Increase maintainability.

Launcher designers have paid relatively little attention to providing the ease and simplicity of assembling or maintaining vehicles. As one OTA workshop participant observed, "One problem with the Shuttle is that the systems on board are not designed for changeout. You can pull a box, but you have to do copper path testing to get it back up there. And on the Shuttle, there are a lot of boxes to fail." Even with ELVs, the amount of testing that is done on the pad requires greater attention to the principles of maintainability. The following would contribute to launch system maintainability:

- *Increase subsystem accessibility.* It would be highly desirable to design subsystems that are more accessible to repair and changeout. One way to assure more accessible subsystems is to include operations people in the design process.

  Such involvement might avoid situations in which some subsystems later turn out to require a lot of detailed inspection and changing, such as the Shuttle main engines, or even the air filters in the Shuttle crew cabins, which collect unanticipated amounts of hair, blue-suit lint, washers, and screws. These subsystems are difficult to access and repair. Even where frequent maintenance has been anticipated, such as in the avionics packages, pulling and replacing electronics boxes requires time-consuming retesting to ensure the integrity of hundreds or even thousands of electrical connections.

  Workshop participants noted that fluid and mechanical systems particularly need more accessible design and an improved capability for making internal tests. A future reusable system might also take a lesson from aircraft design: airliners are designed to have certain parts and subsystems pulled and inspected after a given number of hours of flight. On the Shuttle, however, most subsystems require disassembly, reassembly, and retest after each flight.

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[7] George E. Mueller, Panel discussion, *Space Systems Productivity and Manufacturing Conference IV* (El Segundo, CA: Aerospace Corp., August 1987), pp. 233-35.

[8] U.S. Congress, Office of Technology Assessment, *Low-Cost, Low-Technology Space Transportation Options*, staff paper, in preparation.

- *Design for modularity.* Workshop participants also suggested that as much as possible, components should be modular, standardized and interchangeable. To achieve design modularity means deciding which functions must be handled separately from others and how they must be connected, and even what standards (such as electrostatic discharge protection) must be used. Having standardized interfaces would improve the chances for achieving modularity. This practice is widely used in the design of both military and commercial aircraft. Thus a considerable base of experience already exists.

  Arianespace has attempted to assure that the Titan 3 and the Ariane 4 use similar payload interfaces, because it is in the customers' best interests to have alternative launch vehicles to turn to. In the opinion of one participant, "an absolute mistake on the Shuttle was marrying the payload to the vehicle," which results in major software changes for each flight and complicates the task of remanifesting payloads for other vehicles. Standardized interfaces do, however, exact a marginal cost in performance. Hence they require that payloads be designed slightly lighter and smaller than the vehicle's theoretical maximum capacity. Moreover, it may not be possible to design standardized interfaces across all types of vehicles and missions because the mission requirements for, say, launching into geosynchronous orbit are very different than for low-Earth orbit.
- *Include autonomous, high-reliability flight control and guidance systems.* This technology has yet to be fully developed for space systems, and will be very expensive.
- *Build-in testing procedures, especially for mechanical and fluid systems, as well as for electronic systems.* As noted in a later section, designers already know how to incorporate test procedures in the electronic systems. The biggest hurdle is in the mechanical and fluid systems, which are difficult to test.

Make payloads independent of launcher.

Payload integration constitutes a major fraction of the cost of launch operations. In the Shuttle, payload integration has turned out to be a "long, complex, and arduous task, compared to integrating a payload on an expendable launch vehicle."[9] In large part this complexity results from the potential influence of multiple payloads on each other as well as the interaction of the payloads' weight distribution and electrical systems with launcher subsystems. In the case of the Shuttle, payload customers must also take part in planning and training for deployment or operation of their payloads. Prior to the loss of Challenger, payload integration for the Shuttle typically required about 24 months.[10]

Workshop participants agreed that payloads should be designed to be as independent as possible of the launch vehicle. From the standpoint of the launch system managers, the payload-vehicle interfaces should be standard and incorporate automated checkout procedures, off-line processing, and testing prior to delivery at the launch site. However, such an approach finds few adherents among payload designers, who generally find themselves pushed by the payload performance requirements and weight limitations.

Several workshop participants warned that nothing is gained in reducing overall costs by changes in procedure or technology that merely send problems elsewhere. Many of the ALS and STAS concepts for improved launch operations tend to shift costs from operations to other stages in the launch services process, such as payload processing. For example, requiring payloads to provide their own internal power, rather than relying on a source in the launcher, may reduce ground operations costs, but may also increase the cost of preparing payloads. On the other hand, if launch costs per pound were sufficiently cheap, it might be possible to construct less costly payloads (box 4-C).

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[9] Charles R. Gunn, "Space Shuttle Operations Experience," paper presented at the 38th Congress of the International Astronautical Federation, Oct. 10-17, 1987.

[10] This too is likely to increase with the new safety requirements for the orbiter.

Box 4-C.—Vehicle-Payload Interfaces on the Advanced Launch System

One of the recommendations of the Space Transportation Architecture Study[1] was to eliminate or sharply reduce the burden of supplying special services from the launch vehicle to the payload. This strategy would assist in reducing vehicle turnaround on the pad, which in turn reduces the launch operations costs. ALS study managers have accepted that recommendation and adopted the philosophy that the ALS will provide minimum services to the payload.

Because the payload designers have been severely constrained by the total weight launchers could carry to orbit, their previous practice has been to consider the launch vehicle as almost an extension of the payload, and to expect it to provide a variety of special fittings, upper launch stages, and services such as power, cooling, and fueling. Not only does such an approach lead to extra costs for the launch vehicle itself, it dramatically raises the costs of integrating and launching the payloads. ALS managers also maintain that payloads could be much cheaper to build if the payload designers were less severely constrained by weight capacity of the launch vehicle.

They have asked the payload community to consider the ALS as a transportation system capable of launching high mass payloads safely and on time, but which will provide only standard interfaces and limited services (table 4-2). As one Air Force manager put it, "This won't sit well [with the payload designers] because it's new and it won't be the same way we're doing business now." He went on to say, "We mean to force a revolution in the design of launch vehicles. An evolutionary approach won't reach cost reductions of a factor of ten. It just won't do it."

Participants at two Air Force ALS workshops[2] on the launcher/payload interface were asked to consider and analyze payload designs based on minimum services from the vehicle, and to identify any services they considered essential. In addition, they were asked to consider the effects on payload design of delivering payloads to a ballistic trajectory, just short of orbit. Such a plan would make the launch vehicle much simpler because it would avoid adding rockets to the core vehicle to send it into the ocean after delivering its cargo. However, the payload designers would be required to provide their own boost to operational orbit. In return, they could count on vastly reduced costs per pound to reach space.

Considerably more design work will be necessary to determine whether these stratagems could reduce total launch costs dramatically, and consequently lead to cheaper payload designs. If successful, they could ease many of the current payload design restrictions. For example, with a ten-fold reduction in cost-per-pound to orbit, the weight of the payload and its upper stage could grow by a factor of two and still result in reductions of a factor of five in cost per payload to orbit. In addition, if designers do not have to find innovative but costly ways to shave weight, payloads could be much cheaper to design and build. However, if these tactics lead primarily to shifting most launch costs to the payload accounts, the exercise will prove moot. In addition, if payload weights continue to grow to meet or exceed launch vehicle capacity, costs cannot be reduced. At present, the payload community, especially the designers of highly complicated national security spacecraft, have met the suggestions with profound skepticism (table 4-3).

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[1] U.S. Government, *National Space Transportation and Support Study 1995-2010*, Summary Report of the Joint Steering Group, Department of Defense and National Aeronautics and Space Administration, May 1986.

[2] Held at Aerospace Corp., Los Angeles, CA, November 1987, and January 1988.

SOURCE: Office of Technology Assessment, 1988.

Use less toxic propellants.

Storable high-performance propellants such as nitrogen tetroxide or monomethylhydrazine offer significant advantages where the size of the propellant tanks is an issue, or where propellants must be stored for long periods of time, especially on orbit. These propellants can be used in relatively simple engines and are frequently used for spacecraft as well as for launch vehicles because engines using such propellants can be started and stopped easily.

Although such propellants will continue to have an important role in space transportation, they are also toxic and corrosive, giving rise to human health risks and maintenance problems. Launch personnel must be protected by special suits from

Table 4-2.—ALS Launch Operations Specifications

- Separate launcher preparation from payload preparation
- Place payloads in standard cannisters
- Provide no access to payloads when vehicle is on the pad
- Provide no flight power and communications interfaces

SOURCE: Air Force Space Division, 1987.

Table 4-3.—Launch Vehicle/Payload Interface Issues

- How beneficial is standardization of launch vehicle/payload interface?
- How will needed payload services be provided if minimize services provided by launch vehicle?
- Are total system costs lowered as launch vehicle costs are lowered and vehicle availability enhanced by keeping launch vehicle-provided services at a minimum?
- Can generalized ALS mission analyses provide timely loads and environment analysis to payload?
- Can payload requirements still be met if launch vehicle design is insensitive to payload type?

SOURCE: Air Force Space Division, 1987.

exposure to carcinogenic or corrosive materials. When propellant technicians work with these fluids, other launch personnel must evacuate the area. Toxic propellants also tend to destroy seals and metal containers and create internal leaks. Solving these problems could eliminate a significant amount of ground processing—especially for reusable systems, which require post-flight handling. Developing better materials for storage vessels would help in this effort.

Cryogenic propellants offer lower production costs and higher energy density per pound of propellant. However, cryogenic rocket engines and logistical support are generally more complex and expensive than storables.

Vehicle Technologies

The particular technologies used in a launch vehicle may enhance or hinder ground and mission operations. Table 4-4 provides a list of several advanced technologies that could lower launch operations costs when incorporated in a vehicle.

Table 4-4.—Vehicle Technologies To Facilitate Ground Operations

Built-in test equipment (BITE)
Thermal protection system (TPS)
Fault-tolerant Computers
Autonomous and adaptive guidance, navigation, & control (GNC) system

SOURCE: Office of Technology Assessment, 1988.

Built-in Test Equipment (BITE)

Future launch vehicles are likely to incorporate built-in test equipment and software to detect faults and reconfigure redundant systems; this would thereby reduce ground operations labor and cost. It could also increase vehicle reliability and autonomy during flight, easing mission control requirements. Technology for built-in test of avionics, especially computers, is most mature.

Technology for built-in test of mechanical and fluid systems, especially sensors, will require more development. More reliable sensors could reduce false alarms, and software similar to the expert system KATE (see box 4-B) could diagnose sensor faults.

Thermal Protection System

Reusable vehicles, such as the Space Shuttle, require a thermal system to protect the vehicle upon reentry. As noted in chapter 3, the Shuttle thermal protection system, which was the first reusable system to be developed, has proven expensive to maintain. A more robust thermal protection system would reduce the complexity of inspection and repair and dramatically reduce the costs of refurbishment. Advanced materials, such as carbon-carbon composites and titanium-aluminum alloy, which are being developed for the X-30 program,[11] promise much greater tolerance to the heating and buffeting experienced on atmospheric reentry than do the current Shuttle thermal protection tiles.

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[11] U.S. Congress, General Accounting Office, *National Aero-Space Plane: A Technology Development and Demonstration Program to Build the X-30*, GAO/NSIAD-88-122 (Washington, DC: U.S. Government Printing Office, 1988), pp. 37-38. For a detailed discussion of new structural materials and composites, see U.S. Congress, Office of Technology Assessment, *Advanced Materials By Design*, OTA-E-351 (Washington, DC: U.S. Government Printing Office, June 1988).

Fault-Tolerant Computers

The on-board computers of future launch vehicles could consist of identical computer modules "mass-produced" for economy and connected by optical fibers for reduced susceptibility to electromagnetic interference. These modules could hold software that allows several of them to perform each calculation, compare results, and vote to ignore modules that report "dissenting" results. This approach, now used on the Shuttle in an early version employing less sophisticated computers,[12] would enable the launch vehicle to tolerate failures in one or more computer modules. Computers with a high degree of fault-tolerance would allow the launch of a vehicle with a known fault rather than holding the launch to replace a failed module and retest the system.

The full potential of fault-tolerant computers to reduce maintenance, turn around times, and cost may not be realized until space transportation managers gain sufficient confidence to accept the small risks inherent in launching vehicles with certain known faults. For example, the Shuttle has a quintuple-redundant primary computer system and dual-redundant software for these computers. Shuttle avionics also have triple- and quadruple-redundant sensors. Four of its five computers could fail during flight, or before launch, without causing mission failure. Yet, NASA's highly conservative launch criteria now require all these systems to be operational before the Shuttle can be launched. This increases safety and the probability of mission success, possibly at the expense of economy, resiliency, and access probability. In contrast, airlines will fly aircraft with faulty or failed equipment, as long as the equipment is not vital to safety, or has sufficient redundancy for safe operations.

Autonomous and Adaptive Guidance, Navigation, and Control

Current launch vehicle avionics that perform navigation, guidance, and control must be updated before launch with data such as payload masses and positions within the vehicle, launch time, and predicted winds aloft. Launch delays or changes in weather or payload configuration can require additional updates.

Advanced avionics and software could make the mission software less sensitive to payload configuration and weather, by monitoring a vehicle's response to commands during the early flight stages. For example, an adaptive guidance and control system could estimate payload mass distribution and use the estimate to calculate guidance and control for the remainder of the flight. Similarly, wind could be measured by its effects on vehicle acceleration, trajectory, and structural strain, and control surfaces could be moved not only to steer the vehicle, but also to alleviate structural stresses. A vehicle with these capabilities would not only require less detailed programming before launch, it could also be lighter because it would "know" when to "give" under unanticipated stress. Some current military and civilian aircraft use such systems.[13]

Computer-Aided Design and Computer-Integrated Manufacturing

Computer-aided design and computer-integrated manufacturing can make vehicle design and production faster and probably reduce life-cycle cost even at low launch rates. Computer-aided design techniques can speed vehicle development by automating the distribution, retrieval, and utilization of design information. Computer-integrated manufacturing techniques can reduce production costs by automating selected manufacturing operations.[14] This will require specifically designing systems to facilitate their manufacture by computer integrated methods.

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[12] A. Spector and D. Gifford, "The Shuttle Primary Computer System," *Communications of the Association for Computing Machinery*, vol. 27, No. 9, September 1984, pp. 874-901.

[13] E.g., Airbus Industries A320; tested on the B-52 and F-4.

[14] For example, Hercules Corporation has used automation to increase the speed and safety of its manufacture of solid rocket motors for the Titan IV.

MANAGEMENT STRATEGIES

Without appropriate management strategies, the ability of launch and mission operations managers to utilize new technologies efficiently is likely to be limited. In addition, management strategies that lead to improvements in the ways existing technologies are used could result in cost reductions.[15] This section examines several management strategies that experts have suggested would increase the efficiency of operations and decrease costs.

Facilities

Use an integrate/transfer/launch (ITL) approach.

The ITL method of launch operations (figure 2-9), in which each individual component in the launch process has its own dedicated set of facilities, is essential for achieving high launch rates. Separating the different launch operations functions in this way means that parallel processes, such as payload checkout and vehicle assembly, can proceed at the same time. However, ITL necessarily requires substantial investment in facilities. Further, ITL requires mobile platforms and other facilities for moving launch vehicles along the steps of the process.

Shuttle operations at Kennedy Space Center (KSC) and Titan operations at Cape Canaveral were originally designed to use the ITL approach. By contrast, the launch complexes at Vandenburg Air Force Base require assembly and integration on the pad. Payloads must also be tested and integrated with the vehicle on the pad. Such procedures necessarily limit the rate at which Vandenberg can launch. However, even at KSC and Cape Canaveral, the launch rate for existing vehicles is highly limited, in part because the available facilities are too few and overscheduled to allow the ITL method to be fully realized.

Future launch complexes might be designed to accept several different launch vehicles in the same general size class (figure 4-2).[16] As Arianespace has demonstrated in a limited way, the same launch pad can be used for different launch systems with a minimum of alterations to the launch complex.

Locate manufacturing facilities near launch complex.

Placing the launcher manufacturing facilities near the launch complex would shorten and simplify the launch vehicle supply lines, and eliminate the need for most acceptance testing at the launch complex. However, unless the launch rate was expected to be extremely high, such a strategy might not pay for itself, because it would require substantial capital investment in facilities. In addition, it would require the manufacturing workforce to relocate near the launch complexes.

Use off-shore launch pads.

New locations for launching space vehicles may be needed if demand for launch services increases significantly. Because of restraints caused by lack of suitable real estate and cultural and environmental restrictions, the Air Force and its ALS contractors are studying several off-shore launch concepts, including offshore drilling rigs, small offshore islands, or even mid-Pacific islands. In addition to easing many of the restrictions of coastal launch pads, such options have potential for launching toward all azimuths.

The Air Force is taking a preliminary look at the potential for using offshore drill rigs, because they seem to present greater opportunity for operational flexibility than an island. It is exploring launch pad designs similar to floating oil drilling rigs that could be loaded with a rocket, towed to an offshore site, and, in a matter of hours, turned into a stable launch platform.[17] For this and other offshore possibilities, technical feasibility (especially safe handling of toxic and cryogenic fuels),

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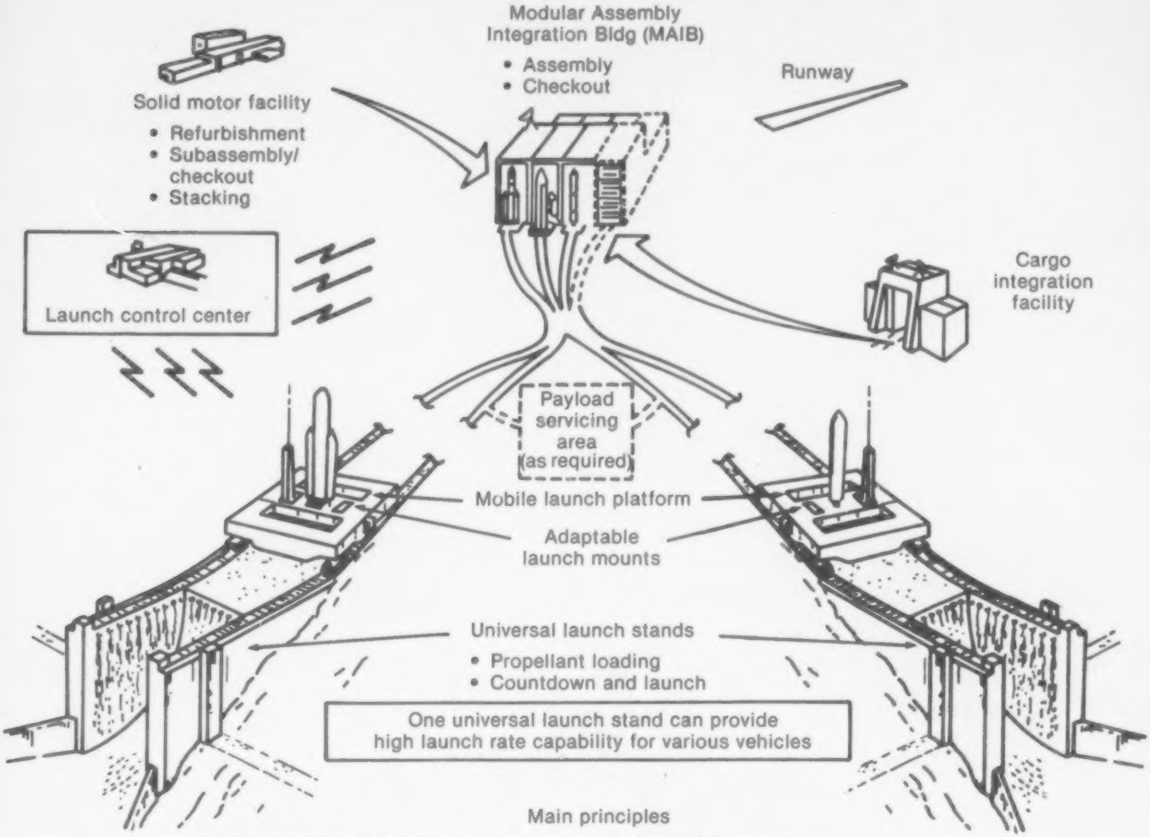
[15] "Space Systems and Operations Cost Reduction and Cost Credibility Workshop," Executive Summary (Washington, DC: National Security Industrial Association, January 1987), p. 2-1,2.

[16] Peter L. Portanova and Harold S. Smith, "Strategic Defense Initiative Launch Site Considerations," Aerospace Corporation Report No. TOR-0084A(5460-04)-1.

[17] "USAF Studies Concept for Launching Heavy-Lift Rockets from Offshore Rig," *Aviation Week and Space Technology*, Feb. 1, 1988, p. 42.

Figure 4-2.—Universal Launch Complex


Modular Assembly Integration Bldg (MAIB)
• Assembly
• Checkout
Runway
Solid motor facility
• Refurbishment
• Subassembly/ checkout
• Stacking
Launch control center
Cargo integration facility
Payload servicing area (as required)
Mobile launch platform
Adaptable launch mounts
Universal launch stands
• Propellant loading
• Countdown and launch
One universal launch stand can provide high launch rate capability for various vehicles

Main principles

- New operational philosophy (enhanced ITL)
- Simplified launch stand sized for largest vehicle
- Minimum time on launch stand
- Containerized cargo
- Rapid recovery capability
- Integrated manufacturing/operations processing on or near launch site
- Adaptable launch mounts (support beams adjustable for vehicle size)

SOURCE: Air Force Space Division.

cost, logistics, and onshore facility and harbor requirements will all need considerable study.

Operations Management

Create incentives for achieving low cost, successful launches.

The current institutional structure tends to penalize launch failure, but is poorly structured to lower launch costs or increase launch rate. Although commercial launch service offerors now have the incentive of competition to encourage them to drive down operations costs, similar incentives are not apparent for Government launches.

Centralize facilities, management, mission control.

One way to lower the overall costs of launch and mission control is to centralize the facilities and personnel. For example, because responsibility for Shuttle launch operations and mission control is divided among KSC, Johnson Space Center, and Marshall Space Flight Center, NASA must duplicate some facilities and personnel, and provide appropriate coordination among centers.

Develop and use computerized management information systems.

Although computer systems play a major part in all parts of mission preparation, launch, and control, they are seldom used for scheduling launch vehicle preparation and keeping track of the status of launch vehicle and payload systems. For the Shuttle at KSC, for example, Shuttle orbiter refurbishment, system status reports, and subsystem alterations are all handled by paper documents. Not only is a paper system more cumbersome and subject to error, it requires considerably more time.

The fundamental difficulty in changing over to a computerized system is that not only would it require the development and installation of a large computer system, it would lead to substantial alterations of the ways in which managers interact with each other. In other words, it would require fundamental changes in the institutional culture of NASA and the Air Force. The computer screen would replace the "in-box."

Increase autonomous operations.

Many operations procedures now carried out by humans, especially routine ones, can be automated to reduce the "standing army" of human operators. Automation could also reduce the time spent in preparing for launch and mission operations, and increase system reliability. However, to be automated, operations procedures must also be standardized.

In fiscal year 1989, NASA's Office of Space Flight will start an Advanced Operations Effectiveness Initiative to focus on automating portions of launch and mission operations (table 4-5). Its goals are to:

- improve the efficiency and productivity of STS operations;
- develop an integrated software strategy;
- develop an autonomous space flight operations software test bed for:
  - —determining enabling technologies for "fully" autonomous operations;
  - —performing hardware/software trade-offs among operational systems;
  - —characterizing flight operations procedures/techniques
- organize existing autonomous capabilities into an integrated system.[18]

NASA's program will serve as a test bed for inserting automated procedures into space transportation operations. It should also assist in making automation more acceptable to launch managers, if it is successful in demonstrating the applicability and safety of autonomous operations.

Table 4-5.—NASA's Advanced Operations Effectiveness Initiative

Kennedy Space Center
- Prelaunch processing/preparation
- Launch operations

Johnson Space Center
- Flight planning/preparation
- Flight control
- On-orbit operations
- Postflight analysis

SOURCE: National Aeronautics and Space Administration, 1987.

ASSESSING TECHNOLOGICAL OPTIONS

Although launch system operations could be improved in a variety of ways, any proposed improvement must meet the test of several measures of merit. Do the intended changes improve efficiency, reduce costs, and/or enhance reliability? Do they contribute to other desired ends, such as improving U.S. economic or political competitiveness? Do they help or hurt the morale of the work force? The primary criteria for judging space transportation system performance and economy include cost, reliability, access to space, and operational flexibility.[19] Proposed changes in launch system operations can be evaluated on the basis of their effects on these criteria.

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[18] NASA JSC Mission Planning and Analysis Division, "Autonomous Spaceflight Operations," briefing to OTA staff, Aug. 5, 1987.

Economic Criteria

Space transportation analysts have used several economic criteria (box 4-D) to judge space transportation system economy. The decisions about which economic criteria to use to evaluate a particular technology for a new system, or for improvements to an existing system, will affect the choice of technology and even of launch system design. For example, selecting new launch systems on the basis of the lowest non-recurring cost generally favors existing technologies and may penalize designs chosen for highest maintainability. The Nixon Administration apparently considered low non-recurring cost as paramount in the initial budgeting for the Space Shuttle,[20] which led in part to a vehicle design that is difficult and expensive to prepare for launch.

On the other hand, selecting minimum recurring cost as the sole criterion may favor technol-

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[19] STAS Joint Task Team, *National Space Transportation and Support Study*, Annex C, May 1987; p. 12, Table 2-3: "Space Transportation Architecture Screening Criteria."

[20] National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technologies Study," (Boeing Aerospace Operations Company), (Kennedy Space Flight Center, NAS10-11344), vol. 1, p. 2.

Box 4-D.—Economic Criteria

nonrecurring costs include costs of vehicle design, development, test, and evaluation (DDT&E), and construction or improvement of facilities for manufacturing vehicles, processing and integrating vehicles and payloads, and mission control. The costs of facilities and equipment existing at the beginning of the accounting period are considered to be "sunk" and are not included in most calculations of net benefit for new systems. Costs of developing technologies should be fully included unless they are being developed for other purposes.

recurring costs include costs of flight hardware (expendable or reusable) and costs of operations and support (e.g., wages). Some recurring costs (e.g., ELV purchases) increase roughly in proportion to the number of launches; Recurring costs such as salaries are moderately insensitive to launch rate.

life cycle cost (LCC) is the sum of the nonrecurring costs and the recurring costs paid to operate a space transportation system for a specified period to transport specified payloads to their operational orbits. Unless otherwise indicated, LCC generally refers to the undiscounted life cycle cost, i.e., the total dollars spent regardless of the year in which they were spent.

present value (PV) LCC discounted at a specified rate to reflect the benefit of not investing for a deferred return. Depending on the goals they wish to achieve, experts differ concerning which discount rate should be used. A 5 percent discount rate (often used in STAS) is considered a reasonable "real" discount rate for use as an adjustment for risk and time preference for government investment[1] but should be increased to adjust for inflation. A 10 percent discount rate was sometimes used in STAS and could be considered the sum of a 5 percent "real" discount rate and a 5 percent inflation rate.

cost risk was defined in STAS as the percentage increase in the present value (of life-cycle cost discounted at 5 percent per annum) which would be exceeded with a subjectively estimated probability of only 0.3.

net benefit is the decrease in present value of life cycle cost that could be obtained by an improvement in a space transportation system, for example, by applying new technology to vehicles, building new support facilities, or changing management methods. The calculated net benefit of an improvement will depend upon the discount rate assumed.

cost leverage: is the net benefit of an improvement divided by the present value of the cost of implementing it. The calculated cost leverage of an improvement will depend upon the discount rate assumed.

internal rate of return (IRR) is the discount rate at which the net benefit of an improvement would be zero.

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[1] Robert C. Lind, *Discounting for Time and Risk in Energy Policy* (Washington, DC: Resources for the Future, 1982).

ogy development with little regard for its cost, if system life expectancy is assumed to be long. The language of the act appropriating fiscal year 1987 supplemental funding for the Advanced Launch System requires NASA and the Air Force to obligate and expend funds "only for ALS variants which embody advanced technologies with a design goal of reducing the cost to launch payloads to low-Earth orbit by a factor of ten compared with current space boosters . . . "[21] Because launch operations account for a substantial percentage of overall launch costs, the agencies would therefore have to reduce these recurring costs significantly.

Present value of life-cycle cost is a flexible criterion that can be made to resemble either nonrecurring cost (by using a high or variable discount rate) or recurring cost (by using a low discount rate). STAS analysts used present value of life-cycle cost discounted at a rate of five percent per annum as the fundamental economic criterion; they also used discount rates of zero percent and 10 percent.

The criteria of net benefit, cost leverage, and internal rate of return (IRR) have been used to identify technologies that could be applied beneficially in a space transportation system. All three criteria have been used for evaluating options for technology development, system design, and management. However, they are not equivalent; options may be ranked differently when evaluated by different criteria. An option may even be judged an improvement according to one criterion and undesirable according to another; an option with a positive IRR would have negative net benefit and cost leverage at discount rates greater than its IRR. For example, Boeing Aerospace Co. estimated that automating the handling and transfer of components for a proposed cargo vehicle would yield an IRR of three or four percent and save $55 million in an SDI deployment scenario, but would have a negative net benefit ($17 million) at a discount rate of five percent, increasing the present value of life-cycle cost by $17 million.[22]

Non-economic Criteria

Several non-economic criteria have been used to rate space transportation system performance (table 4-6 and app. B).[23] In addition, other non-economic criteria, such as international technological, political, or economic leadership, are often employed in choosing among competing paths.

Because both ground operations and mission operations are integral parts of the launch system, they play significant roles in meeting the non-economic, as well as the economic criteria. For example, the Titan 34D fleet had low operational availability for 1986 and most of 1987 as the result of the failure of a liquid fuel pump and a solid rocket motor respectively, and of standdown policy. During the standdown of the Titan, the Air Force developed non-destructive testing methods to test the rocket motors prior to assembly. These methods are now in use at Vandenburg and at Cape Canaveral.

The example of non-destructive testing illustrates the tradeoff among economic and non-economic criteria. Although developing and installing these methods of testing were relatively expensive and will increase the costs of preparing a Titan for launch, the perceived improvement

Table 4-6.—Non-economic Criteria for Judging Space Transportation System Performance

- *Capacity*—maximum annual launch rate or payload tonnage to given orbits.
- *Flexibility*—ability of a launch system to meet alterations of schedule, payload, and situation, and to satisfy missions in more than one way.
- *Reliability*—the probability with which a system will perform an intended function successfully.
- *Resiliency*—the ability of a space transportation system to adhere to launch schedules despite failures—to "spring back" after failure.
- *Operational Availability*—the probability that a fleet, or a multi-fleet system, will be operating (i.e., not standing down).
- *Access Probability*—the probability that a launch system can launch a payload on schedule and that the payload will reach its operational orbit intact.

SOURCE: Office of Technology Assessment, 1988.

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[21] Fiscal Year 1987 Supplemental Appropriations Act: Public Law 100-71.

[22] USAF Space Division, *Launch Systems for the Strategic Defense Initiative—Data Book* (Los Angeles Air Force Station, CA: Headquarters, U.S. Air Force Systems Command Space Division, December 1986), pp. 7-22 and C-9.

[23] Other criteria used in STAS are defined in Joint Task Team, *National Space Transportation and Support Study 1995-2010*, Annex E ("DoD Functional/Operational Requirements"), May 1986, p. 5, and Annex C ("Space Transportation Architecture"), p. 12, Table 2-3 ("Space Transportation Architecture Screening Criteria").

in access probability was considered to outweigh the costs incurred.

Economic Benefits

Several contractors participating in the Space Transportation Architecture Study estimated the economic benefits[24] to U.S. space transportation of developing or applying technologies to facilitate ground operations. Table 4-7 illustrates one set of estimated benefits.[25] The technologies assessed include some that would be used in launch vehicles (e.g., built-in test equipment) and others that would be used in ground support equipment or facilities (e.g., automated data management system). The technologies of table 4-7 are considered "enhancing" technologies—they reduce costs in the assumed demand scenario but are not required to build or operate the chosen mix of launch vehicles and facilities.[26]

The benefits of each technology are estimated in terms of three criteria: internal rate of return, undiscounted net benefit, and net benefit discounted at 5 percent per annum. The technologies are listed here in order of their estimated internal rates of return. As the table illustrates, if they were ranked according to undiscounted or discounted net benefit, the order would differ. For example, "expert systems" rank highest in undiscounted net benefit but tenth in internal rate of return. The benefits are sensitive to changes in mission model, discount rate, or mix of launch vehicles.

Similar estimates by other contractors differ in detail but generally predict that development of these technologies would be beneficial. Table 4-8 compares internal rates of return estimated by Boeing Aerospace Co.[27] with estimates by the Space Systems Division of General Dynamics.[28] Comparison of the two sets of estimates is complicated because the two companies defined technology categories differently. For example, Boeing defined a category it called built-in test equipment (BITE), while General Dynamics included BITE used for pre-flight testing in a category it called automated ground operations and BITE used for in-flight testing in a category it called flight management systems. The flight management systems and automated ground operations categories included equipment other than BITE. For example, flight management systems

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[24] These estimates apply only to U.S. space transportation expenditures. Benefits of technology transfer to other sectors is difficult to estimate even a posteriori; see NASA Advanced Technology Advisory Committee, *Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy*, NASA-TM87566, March 1985, vol. II, p. 104. It would be very difficult to forecast spin-off benefits from the technologies described above, and OTA knows of no such forecast.

[25] Boeing Aerospace Company; from *Space Transportation Architecture Study, In-Progress Review Number 5* (Seattle, WA: Boeing Aerospace Company, Apr. 7, 1987), p. 209.

[26] The mix assumed in table 4-7 features a new piloted orbiter, a flyback booster, and a cargo vehicle core stage with a recoverable propulsion/avionics module.

[27] Boeing Aerospace Company, op. cit.

[28] General Dynamics Space Systems Division, *Space Transportation Architecture Study, Special Report—Interim Study Results*, report GDSS-STAS-87-001 (San Diego, CA: General Dynamics Space Systems Division, May 12, 1987), vol. 2, book 3, pp. 7-90 - 7-91.

Table 4-7.—Estimated Economic Benefits of Developing Technologies to Facilitate Ground Operations ("Normal Growth" mission model)

Technology	Internal rate of return	Net benefit (undiscounted)	Net benefit (discounted 5% p.a.)
Built-in test equipment	140.0%	$2,617M	$911M
Automated data management system	115.0	1,898M	709M
Automated test and inspection	61.0	1,454M	498M
Accelerated load calculations	19.5	247M	48M
Thermal protection system	16.0	218M	59M
Fault-tolerant computers	15.5	106M	30M
Automated launch vehicle and payload handling	15.0	830M	227M
Database management system	13.5	5,413M	1,472M
Computer-aided software development	12.5	2,225M	552M
Expert systems	11.5	5,775M	1,372M
Autonomous and adaptive guidance, navigation, and control system	6.0	716M	- 43M

NOTE: Not endorsed by OTA; sensitive to architecture and mission model.

SOURCE: Boeing Aerospace Co.

Table 4-8.—Technology Development Benefits: A Comparison of Estimates by Two STAS Contractors
("Normal Growth" mission model)

Boeing Aerospace Co. proposed vehicles		General Dynamics proposed vehicles	
Technology	IRR	IRR	Technology
Fault-tolerant computers	15.5%	43.4%	Flight management systems
Built-in test equipment[a]	140.0%	9.1%	Automated ground operations
Automated test and inspection	61.0%		
Automated component handling	15.0%		
Automated data management system[b]	115.0%	17.8%	Advanced information processing
Database management system[c]	13.5%		
Expert systems	11.5%	30.5%	Expert systems
Accelerated load calculations	19.5%		
Computer-aided software development	12.5%	21.8%	Automated software generation and validation
Thermal protection system	16.0%	21.7%	Reusable cryogen tankage
Autonomous, adaptive guidance, navigation, and control system	6.0%	31.1%	Adaptive guidance, navigation, and control
Kerosene engine	NA[d]	4.1%	Liquid oxygen/hydrocarbon engine
Actuators	NA[d]	1.9%	Precision recovery
Hang gliders	NA[d]		

[a] General Dynamics included built-in test equipment et al. in two categories: flight management systems and automated ground operations.
[b] For ground operations.
[c] For mission control.
[d] Not assessed: Boeing assumed this technology to be enabling—i.e. necessary for its recommended architecture—and assessed its net benefit but not its IRR.
[e] Not assessed: General Dynamics assumed this technology to be enabling—i.e. necessary for its recommended architecture—and did not assess its IRR.

SOURCES: Boeing Aerospace Co. and General Dynamics Space Systems Division.

included fault-tolerant computers, which Boeing defined as a separate category.

In table 4-8, OTA attempted to group overlapping technology categories. For example, the first group of rows includes four categories defined by Boeing and two, covering the same applications, defined by General Dynamics. The second group of rows includes the Boeing categories "automated data management system" (for ground operations) and "database management systems" (for mission control) and the General Dynamics category "advanced information processing" (for both ground operations and mission control). The third group of rows includes the Boeing categories "expert systems," and "accelerated load calculations" and the General Dynamics category "expert systems," which would include expert systems for load calculations. For those technologies that can be compared (e.g. "computer-aided software development" versus "automated software generation and validation"), the estimated internal rates of return differ because of differing vehicle concepts, technology application concepts, estimation techniques, databases, and judgments.

The economic benefits of so-called "enabling" technologies, which are required in order to build a given mix of launch systems, can also be estimated. For example, figure 4-3 displays estimates of the undiscounted net benefits of four technologies that, if developed, would enable the Nation to develop a mixed fleet of advanced vehicles proposed by Boeing Aerospace Co.[29] Boeing estimated the undiscounted life-cycle cost of the reference launch system mix (featuring the Shuttle for manned flights and Titan IV for cargo) to be $248 billion in the STAS "normal growth" scenario. Developing kerosene-burning rocket engines, reusable liquid hydrogen tanks, actuators for the control surfaces of reusable vehicles, and Rogallo wings and control systems ("hang gliders") to return propulsion/avionics modules to the launch area, would enable the United States to build new kinds of vehicles that could carry the assumed traffic for $197 billion—about $50 billion (21 percent) less than the reference mix would cost.

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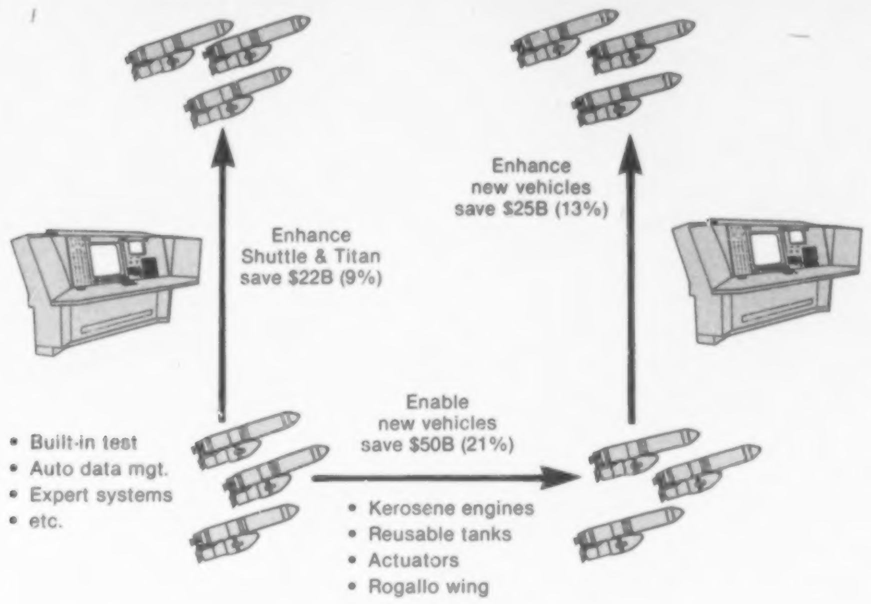
[29] This vehicle mix features a new piloted orbiter, flyback booster, and cargo vehicle core stage with recoverable propulsion/avionics module.

Figure 4-3.—Economic Benefits of Emerging Technologies


Enhance
Shuttle & Titan
save $22B (9%)
Enhance
new vehicles
save $25B (13%)
Enable
new vehicles
save $50B (21%)
• Built-in test
• Auto data mgt.
• Expert systems
• etc.
• Kerosene engines
• Reusable tanks
• Actuators
• Rogallo wing

SOURCE: Office of Technology Assessment. Based on estimates by Boeing Aerospace Co.

The figure also displays Boeing's estimates of the undiscounted net benefits of applying ground-operations technologies and other technologies[30] to enhance a launch system. Enhancing the reference launch system would save $22 billion, or 9 percent of $248 billion. Using the same technologies to enhance operations of advanced vehicles embodying the chosen enabling technologies would save $25 billion, or 13 percent of $197 billion. The total savings afforded by enabling new vehicles to be built and then enhancing their operations is estimated to be $76 billion or about 70 percent of the undiscounted life-cycle cost of the reference Shuttle-Titan IV launch system. The enhancing technologies would save $3 billion more if applied to the new launch system (as Boeing recommended) than if applied to the reference launch system, an example of synergism between the enabling and enhancing technologies.

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[30] The enhancing technologies include some (e.g., expendable aluminum-lithium tankage), which would not significantly affect ground operations but which could reduce life-cycle costs in other ways.

Chapter 5

Operations Policy

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Chapter 5

Operations Policy

As previous chapters emphasize, substantially increasing the efficiency of space transportation operations, and reducing costs, will require improvements in both management strategy and the application of technology. Neither alone will be sufficient. Reducing costs will also require greater attention to launch and mission operations within the National Aeronautics and Space Administration (NASA) and the Air Force, and oversight by Congress. Although modest reductions in operations costs are possible for existing launch systems, new launch systems, especially designed for low-cost operations, appear to offer the potential for significant savings. The following discussion explores several policy options for putting the necessary technologies and management strategies to work.

IMPROVING OPERATIONS FOR EXISTING SYSTEMS

The current U.S. launch fleet consists of a range of vehicles and systems capable of placing from 440 to 40,000 lbs. into low-Earth orbit. Even if Congress funds development of a new launch system to be built in the mid to the late 1990s, the United States will continue to use most of the current fleet (with relatively minor modifications) until the beginning of the 21st century.[1] Operating the existing systems will be expensive. For example, the Shuttle system will cost the U.S. taxpayer approximately $2.5 to $3.5 billion per year (1988 dollars) for the foreseeable future.[2] Of this, some $1.5 to $2.0 billion per year will be devoted specifically to ground and mission operations. Annual operations costs for the ELV fleet could total $120 to $150 million.[3]

Congress could assist efforts within the Air Force and NASA to reduce operations costs of current systems by using its legislative authority to require both NASA and the Air Force to purchase launch services, rather than vehicles, from private industry. Reducing costs for Government-operated launch systems is inherently difficult because Government lacks the cost saving pressures of a competitive market environment. Nevertheless, Congress could help by requiring NASA and the Air Force to charge the costs of ELV launches to the program that uses or "owns" the payload. Congress could also use its oversight authority to conduct site visits focused on launch and mission operations, hold hearings on cost reductions, and mandate reports to Congress on the agencies' efforts to reduce operations costs.

Purchasing Launch Services Rather Than Vehicles

The Administration's latest space policy, which was released February 11, 1988, specifically directs NASA and other civilian agencies to purchase launch services rather than launch vehicles for expendable launchers, unless they require the use of the Titan IV, which is under Air Force ownership and control.[4] This policy is intended to assist the development of the private launch industry by putting the private sector in charge of the production and operation of most expendable launch systems. The policy should also have the effect of lowering operations costs for these launch systems, if launch services are procured competitively and if launch companies are given the authority to determine the most cost-effective operations methods, consistent with safety and reliability.

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[1] U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

[2] U.S. Congress, Congressional Budget Office, *The 1988 Budget and the Future of the NASA Program*, Staff Working Paper, March 1987.

[3] Based on an annual launch rate of six Titan IVs, 4 Delta IIs, and 4 Atlas-Centaurs.

[4] "Civil Government agencies will encourage, to the maximum extent feasible, a domestic commercial launch industry by contracting for necessary ELV launch services directly from the private sector or with DoD." White House, Office of the Press Secretary, "Fact Sheet," Feb. 11, 1988, p.9.

For national security space activities, the President's space policy allows the Department of Defense (DoD) to procure either ELV launch services or launch vehicles.[5] Congress could strengthen these two policies by including them in legislation. Congress could expand space transportation policy and encourage private sector competition by directing the Air Force and other national security agencies to purchase launch services rather than vehicles for all expendable launches, including the Titan IV. Such a policy would require turning over the responsibility for the operation of the Titan IV and any new launch systems to private industry.

Charging Payload Programs the Costs of Services

Space transportation costs make up a significant fraction of the total cost of a payload mission, yet within NASA and the Air Force the budget for payload design, development, and construction is independent of the budget for space transportation services. Thus, payload program managers have little direct incentive to seek reductions in transportation hardware or operations costs. One way to reduce operations costs over the long term, especially for existing systems, would be to require NASA and the Air Force to charge each payload program the recurring costs of transportation services provided. Such a policy would enable each agency and the Congress to develop a more realistic picture of the overall cost of a scientific or applications program. If payload managers had to pay for launch services out of their payload budgets, they would have greater incentive to encourage designers to design payload/vehicle interfaces that are cheaper to integrate ~~and ser~~vice.

This policy would be more effective for ELVs than for the Shuttle, because the latter is still undergoing considerable modification and many of the costs for the Shuttle are development costs. In addition, a large portion of the investment in the Shuttle is in the reusable orbiters, which function both as space platforms and launch vehicles. Apportioning costs of the Shuttle to the different users would also raise the question of competition between using the Shuttle and using an ELV.

Congressional Oversight

Reducing the operations costs of existing launch systems will require a series of evolutionary steps involving new technology and incremental changes in management strategies. Inserting new technology into current space transportation operations is costly and time-consuming. The complex procedures and myriad rules of launch and mission operations that have evolved over 30 years of the publicly funded space program are extremely difficult to change significantly, even for a new launch system, because they are so complex and interrelated, and require such varied human skills. Altering one aspect of a launch system forces other parts to change, often unwillingly. Because of these complex human and technological interactions, operations managers tend to be highly conservative in adopting proposed changes in launch procedures. Reducing operations costs will require the willingness of NASA and Air Force management to focus continual attention on inserting new cost-saving technology and innovative management strategies into operations processes. It will also require congressional oversight to assure agencies' attention to cost reduction strategies and consistent funding by Congress.

Changes of management strategy alone can yield significant savings in operations costs (see also ch. 2). For example, the Strategic Defense Initiative experiment Delta 180, which was flown on a Delta launch vehicle, demonstrated that reducing NASA and Air Force oversight and reporting requirements can decrease launch operations costs.[6] These requirements work against contractor innovation because launch services companies find it easier to keep the payload customer happy with the same "tried and true methods" than to change them. Current requirements reduce the potential for applying new technologies to launch operations and raises the cost of launch services to the Government.[7]

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[5] Ibid., p. 8.

[6] Department of Defense Strategic Defense Initiative Office/Kinetic Energy Office, "Delta 180 Final Report," vol. 5, March 1987.

Congress could assist the introduction of more efficient management methods by directing NASA and the Air Force to reduce their direct involvement in the launch process, especially for expendable launch vehicles. Congressional attention in the form of site visits, hearings, and reports to Congress would play an important part in assuring that such direction is carried out effectively. In this, as in other areas of congressional oversight, Congress should be cautious not to burden the agencies with reporting requirements that inhibit the agencies' ability to conduct efficient operations.

FUTURE LAUNCH SYSTEMS

The most promising means of reducing the operating costs of launch systems is to develop a new system specifically designed with that goal uppermost. The Air Force and NASA are currently working on an Advanced Launch System (ALS) program with the goal of reducing the cost of launch per pound by a factor of 10 over current costs. Efficient, cost-effective ground operations are essential elements of the ALS Program, but would require considerable initial investment in new facilities and operations technology in order to realize the benefits of the ALS designs currently proposed. ALS planners are developing vehicle designs that incorporate rapid, low cost vehicle processing. Carrying out the goals of the ALS program would also require implementing a management philosophy that stresses the importance of low-cost operations.

If Congress wishes to lower the operational costs of future launch systems significantly, it must be willing to appropriate funds for the necessary launch operations facilities as new systems are developed. New launch pads and associated facilities would be needed. Many of the current inefficiencies in U.S. launch systems are the result of adding to or improving existing aging facilities. For example, many of the facilities at Johnson Space Center and Kennedy Space Center were originally built in the 1960s for Saturn 5. The Shuttle launch complex SLC-6 at Vandenberg Air Force Base was modified from a facility originally built for the Air Force's Manned Orbiting Laboratory, a program that was canceled in the early 1970s.

Some analysts have argued that the next major space transportation system, designed for low-cost operations, should be funded in a multiyear procurement that would require Congress to commit the country's resources over a period of several years, just as it does with certain weapons systems. Such a multiyear procurement could allow for larger production runs of launch vehicles and major investments in new launch operations infrastructure. This strategy could reduce the cost per unit vehicle, and provide additional incentives to design and build modular facilities capable of being modified to accommodate new technology. A recent study by the Congressional Budget Office has shown that where the development and procurement of weapons systems has been stretched out, whether because of Administration or congressional action, costs of weapons have risen.[8] The Space Shuttle program provides an excellent example of this phenomenon in the civilian space program.

However, as the OTA Special Report, *Launch Options for the Future: A Buyer's Guide*, points out,[9] such a strategy would also require the Administration and Congress to agree on long-term goals for the space program and a level of funding to support such goals.[10]

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[7] As one launch company official that OTA queried put it, "it costs in two ways. NASA hires more people than it needs to, and we [the launch company] have to hire extra people to respond to NASA's concerns."

[8] U.S. Congress, Congressional Budget Office, *Effects of Weapons Procurement Stretch-Outs on Costs and Schedules* (Washington, DC: U.S. Government Printing Office, November 1987).

[9] U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

[10] See U.S. Congress, Congressional Budget Office, *The NASA Program in the 1990s and Beyond* (Washington, DC: U.S. Government Printing Office, 1988) for a comprehensive discussion of the budgetary impacts of different development paths for the civilian space program.

TECHNOLOGY RESEARCH AND DEVELOPMENT

Research and development efforts have a continuing role in reducing costs of space transportation. The Space Transportation Architecture Study[11] and OTA's own examination of space transportation have provided a substantial list of technologies that could serve as a foundation for improved launch efficiency and lower operations costs (tables 4-1 and 4-4). Because many of these technologies would be related to those required for operating ELVs, the Shuttle or even a space station, the various governmental programs could be closely linked. For example, research devoted to the development of autonomous systems for handling hazardous substances for the Shuttle and expendable launchers could be applied to similar systems for a space station.

In order to accomplish the goals of increasing efficiency and reducing costs, Congress could authorize, and appropriate funds for, a technology development and insertion plan specifically directed toward these goals. OTA workshop participants supported the development of a national strategic technology plan designed to improve launch technologies for a wide range of launch problems and activities. A national plan would also provide intragency and interagency coordination in order to reduce any duplication of research and development being done in NASA and the Air Force.

Part of this national plan should be directed specifically at launch operations. "We need long-term objectives," said one participant, "which are handed down from the highest levels to determine where we go with the technology. I think that today a great deal of money is spent and invested in shotgun development that really has a limited yield. Budget constraints are real and are here to stay. With a well-developed strategic plan, you can accomplish a lot more with the same money that is being spent in the agencies today." Such a plan would enable NASA and the Air Force to coordinate their efforts and to focus on a variety of technologies having both near and far term payoffs.

Since the early 1970s, when NASA decided to focus its space transportation efforts on the space shuttle, the United States has invested very little in technologies that would lead to improving the efficiency and reducing the costs of launch operations procedures and payload processing. NASA's Civil Space Technology Initiative, and the Air Force and NASA Focused Technology Program that is part of the ALS program (see ch. 2, Issue B) could contribute to achieving these goals. However, they do not spend enough effort on inserting technology into operations.

A thoughtfully constructed technology development plan would generate an ongoing program of incremental improvements to launch vehicles, facilities, and launch operations. One of the goals of such a program should be to develop operations technology and procedures designed to foster routine launching. It would assist the need for improvements in current vehicle systems and support research and development of operations for advanced vehicles. A technology development plan should include work in all phases of technology development:

- *broad technology exploration (basic research)*—in areas of potentially high payoff such as automation and robotics, built-in-test procedures, and fault tolerant computers;
- *focused research leading to a demonstration*—of flight or ground operations systems such as avionics packages, expert systems, automated inspection systems; and
- *implementation to support specific applications*—in day-to-day operations. This phase should also include the development of methods to insert such technology with minimum disruption to existing procedures.

Even without a national technology plan, Congress could assist the integration of new technologies into Shuttle launch operations by providing modest additional funding specifically for a NASA technology insertion program. In addition, it could hold hearings to assess the progress NASA and the Air Force are making in coordinating existing research and development programs for launch and mission operations.

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[11] U.S. Government, *National Space Transportation and Support Study 1995-2010*, Summary Report of the Joint Steering Group, Department of Defense and National Aeronautics and Space Administration, May 1986, pp. 15-19.

Congress could also enhance the development of new operations technologies by funding an operations test center specifically designed to carry out tests of new technologies for incorporation into existing and new launch systems (see *The Role of the Private Sector,* below).[12] Such a center would consist of a mock launch complex and the necessary supporting facilities for testing new concepts and technologies outside the flow of normal launch operations. It could enhance both the CSTI and the ALS Focused Technology Program and could also demonstrate the insertion of new methods, techniques, and equipment into existing launch systems.

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[12] As part of its study of ALS for the Air Force, General Dynamics Space Systems Division has specifically suggested turning Launch Complex 13 at Cape Canaveral into an "ALS Operations Enhancement Center," which would be available to the entire aerospace industry—General Dynamics briefing to OTA, Mar. 15, 1988.

ESTIMATING OPERATIONS COSTS

As noted in chapter 4, projected future savings in operations costs will have to be examined carefully to assure that the costs of making the proposed changes (up-front, fixed costs) are less than the savings realized in recurring costs over the life of the program. To accomplish this, design and development of improvements to operations will require adequate cost estimation models in order for the agencies and Congress to make informed decisions about whether the proposed improvements meet cost reduction goals. As noted in chapter 3, existing cost estimation models have proven grossly inadequate in estimating operations costs. Workshop participants urged that new cost-estimating models be developed. Although the current ALS Program includes funding to support the development of accurate cost models, congressional oversight may be required to assure that the agencies focus on this issue.

Congress could require that the Air Force and NASA report on their progress in developing more accurate cost estimating models. As pointed out in chapter 3, many of the data that could be used to verify the accuracy of new models have not been gathered, particularly for launch operations. In part this has been the result of congressional and Administration cost-cutting measures. However, such measures only inhibit future cost estimation, because reliable models cannot be developed without access to this important information. Collecting and maintaining such data could be much cheaper in the long run than attempting to make decisions based on incomplete information. NASA and the Air Force should require contractors to provide this information.

A new cost estimation model should be as free as possible of potential bias. To avoid such bias, or a more direct conflict of interest, **it may be appropriate to task an independent agency such as the National Academy of Sciences, or the General Accounting Office, to develop an independent cost model.**

THE ROLE OF THE PRIVATE SECTOR

One of the difficulties the Government faces in establishing its own programs to reduce costs is that such programs generally lack the sort of incentives provided by the competitive environment of the marketplace. Until recently, the development and operation of U.S. launch vehicles were the sole responsibility of the Government. Now, however, three private U.S. firms offer commercial launch services on ELVs originally developed with Government funding—General Dynamics (Atlas Centaur), Martin Marietta (Titan), and McDonnell Douglas (Delta). In addition, three startup companies are also marketing space launch services—Space Services, Inc. (Conestoga), Orbital Sciences Corporation (Pegasus) and Amroc Corporation (Industrial Launch Vehicle).

The French firm Arianespace, the Soviet Union, and the Peoples Republic of China also offer a wide range of ELV services.

Competition among U.S. firms, and with foreign launch companies, which receive substantial government subsidy, may eventually spur U.S. firms to invest in additional facilities and technologies for reducing the cost of launch operations. However, the industry is not yet involved enough in developing new operations technologies.[13] Two primary factors in the existing institutional arrangements for launch operations impede privately funded innovations.

First, private launch firms only have incentive to invest in new facilities and technologies for reducing costs if the up-front investment leads to sufficient future profits. Yet launch demand for commercial payloads in the mid-1990s does not appear large enough to foster such private investment today.

Second, all current ELV launch facilities, including the safety and range components, are owned and operated by the Air Force. Private firms lease them for commercial launches on a cost reimbursable basis. Although industry can institute some cost savings measures in launch operations at these Government-owned facilities, they are constrained by the necessity to deviate as little as possible from procedures and facilities used for launching government payloads. To do otherwise would not in general be cost-effective. Unless the government encourages such investment by removing unnecessary barriers of documentation and reporting and rewarding innovation, launch firms are unlikely to assume such risks on their own.

The Government could stimulate the innovative power of the launch industry by purchasing services rather than systems; providing incentives for developing new, cost saving methods; and by providing a Government-funded operations test bed.

Purchasing Services

In 1985, Congress appropriated funds for the Air Force to procure an improved Titan launch vehicle (the Titan IV) to serve as a backup to the Shuttle for critical DoD payloads. By committing to purchase several vehicles at once in a "block buy," the Air Force saved money. Although the Air Force purchase of the Titan IV has stimulated the domestic ELV launch industry and resulted in savings on vehicle hardware, it has not reduced operations costs very much. In a truly competitive environment, relatively high demand for Government payloads could lead to reduced operations costs, especially if private firms had greater control over launch operations. However, block buys are not in themselves likely to result in savings on launch operations, because the Government still controls the manufacturing and launch processes.

More recently, the Air Force conducted a competition to purchase a lower capacity Medium Launch Vehicle II (MLV-2). This purchase represents a different strategy in which the Air Force purchases launch *services* rather than vehicles. Under this form of purchase, the Government treats launch service providers much as it treats competitive commercial procurements from any other service industry, and pays for the delivery of a payload to a specified orbit. The launch services company provides the launch vehicles and all supporting services, including launch operations. Government officials work with the launch firm to assure that the firm meets Government standards of manufacture and service. However, they limit their involvement in the details of the manufacturing and launch process. The launch firm, not the Government, accepts the financial risk of a launch failure, and guarantees a reflight or other compensation. However, because a launch failure would mean losing an expensive payload as well as a vehicle, Government officials have strong incentives to maintain current levels of launch operations oversight despite attempts to reduce oversight. They are concerned that the risk of failure and a subsequent free reflight may not be sufficient discipline for the launch firm.

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[13] "Space Systems and Operations Cost Reduction and Cost Credibility Workshop," Executive Summary (Washington, DC: National Security Industrial Association, January 1987), p. 2-22.

General Dynamics Corporation, which won the Air Force MLV-2 competition, will provide 11 Atlas-Centaur-2 launchers and associated launch services for a firm fixed price of about $40 million each. The Government will rely on a delivery schedule, performance, and reliability guaranteed by General Dynamics. If the launcher fails for reasons associated with manufacture or preparation, General Dynamics guarantees a reflight. This arrangement will require fewer Government oversight personnel and give General Dynamics a financial incentive to improve the efficiency and reduce the costs of launch operations. Although precise figures for the savings involved are impossible to derive because this version of the Atlas-Centaur has not existed before, company spokesmen estimate this method of procurement resulted in savings to the Government of 12 to 20 percent. Savings of this magnitude are possible both because the Government makes a "block buy," which reduces the cost of manufacturing each vehicle, and because the Air Force will not be overseeing the Atlas-Centaur production line.

Purchasing launch services rather than vehicles has not resulted in immediate savings in launch operations, in part because the Air Force still manages the launch pads. Additional savings should be possible as experience with this method of providing launch services grows. For the purchase of launch services to be most effective, the Government will have to carry through with its resolve to reduce oversight to a minimum and give private firms greater control over launch operations. Under the terms of a fixed price services contract, tasks outside the scope of the contract, such as increased documentation and reporting requirements, will cost the Government more.

Government purchases of commercial launch services offer the potential for synergism between Government and private sector attempts to reduce operations costs. The large Government purchases give private industry an assured financial base from which to work in competition with foreign firms. As the U.S. launch industry begins to demonstrate cost reductions in its commercial launch operations, some of these gains may be transferable to Government launch operations.

Incentives for Reducing Costs

OTA workshop participants pointed out that the Government agencies had been less innovative than they might have been in providing contractors with direct incentives to lower the costs of launch operations. In part, this is the result of their historical focus on the performance and safety of launch vehicles, and a desire to limit initial investment, rather than on reducing long-term operations and maintenance costs.[14]

As the Delta 180 program demonstrated, cash incentives for meeting schedules can be an effective means of increasing launch operations performance (see Issue A, ch. 2). The Government could explore other possible incentives for reducing costs. Existing types of incentives do not specifically address the reduction of operations costs.

Launch Operations Test Center

As noted in the section above on *Technology Research and Development*, a space transportation operations test center could assist innovation in operations technology. NASA currently operates several aeronautics test facilities, which the aircraft industry uses on a fee basis. For example, the NASA Wallops Island facility maintains a runway and associated test facilities for assisting the private sector in improving the landing and flying characteristics of commercial aircraft. Such a facility could be operated as a Government-owned, contractor-operated establishment.

Alternatively, Congress might deem it appropriate to establish a center that is funded in part by the private sector. Such a center could be operated by a private consortium that brought together experts from private companies, the Government, and the university community.

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[14] National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technology Study," KSC Report NAS10-11344, Boeing Aerospace Operations Co, May 4, 1987, p. 2.

Congress could also direct the Air Force and NASA to fund research within private firms to examine ways of reducing the weight and complexity of payloads. As noted in chapter 4, launch vehicles are only part of the equation for obtaining assured access to space. If launch operations costs are to be reduced significantly, there must be a complementary emphasis on reducing payload costs and simplifying payload designs. The private sector could help with these. A wide variety of new ideas have surfaced with the DoD Lightsat[15] and ALS programs. These and related ideas should be examined for their potential applicability to lowering launch operations costs.

INSTITUTIONAL POLICY

Attempts to reduce operating costs in planning a new launch system would be more effective if those responsible for managing launch and mission operations and facilities were directly involved throughout the design and demonstration process. However, they must not only be involved in these processes, but have the institutional influence, or "clout," to make their views heard and acted upon. Giving operations experts broader influence over launch system planning and design will require substantial changes in the "institutional culture" of NASA and the Air Force.

New Unpiloted Launch Systems

As pointed out in chapter 4, to reap the potential gains offered by revolutionary changes in technology will also require revolutionary management changes. However, the United States is not likely to achieve the desired result if the current institutional structures of NASA and Air Force are left intact. One way to effect change in the institutional culture of launch operations and give operations personnel more influence in launch system design would be to separate the responsibility for system design and development from the operations responsibility. For example, **Congress could decide to fund development of a new launch system under the management of the Air Force and NASA with the understanding that the operation of the new launch system would be conducted by the private sector**. Under such an arrangement, the launch company would commence operation after the completion of development flights and would provide launch services to the Government on a contractual basis. In order to encourage attention to cost reduction, the company would also be encouraged to market its services to other payload customers, either from the United States or abroad.

The European Space Agency has found such an arrangement effective. When planning for the development and operation of the European Ariane launcher,[16] the European partners decided early to separate the functions of launcher development and operation. ESA, using the French space agency CNES as technical manager, has devoted its efforts to building an efficient, low-cost vehicle; Arianespace, S.A., a private French corporation,[17] has focused on developing cost-effective operations (figure 5-1). Arianespace markets the Ariane launcher and provides launch services. Neither institution can proceed without the help and expertise of the other, but each contributes to the development of an efficient launch system. The result has been a relatively simple vehicle that can be prepared and launched quickly with a minimum of personnel.[18]

The Ariane example presents an attractive model for launch operations because it created a substantive division between the responsibility

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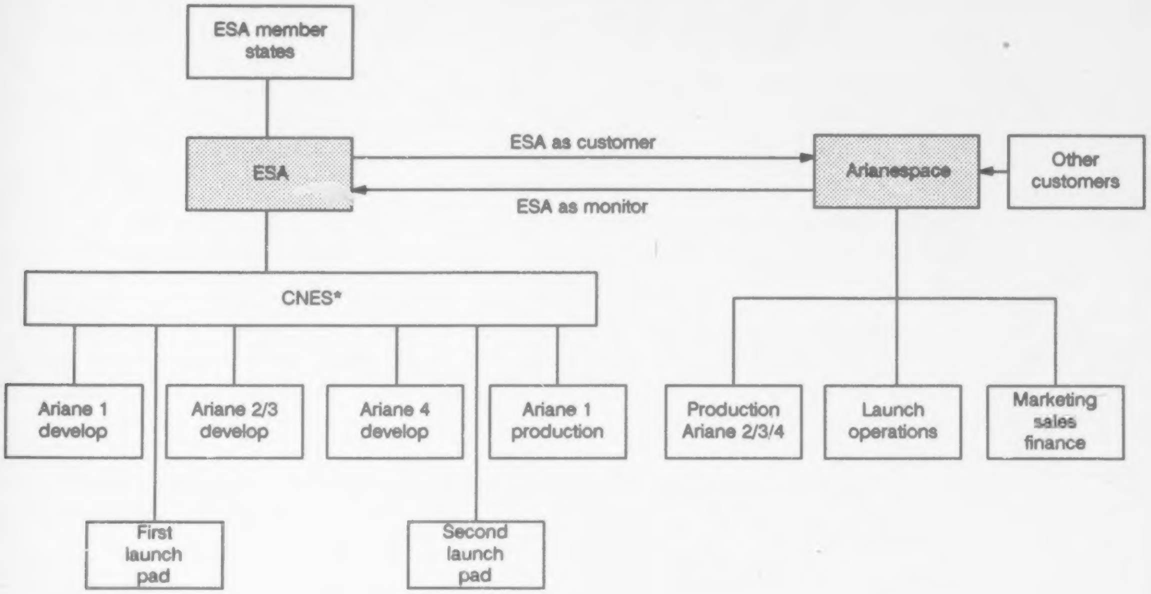
[15] The Lightsat program, funded by DARPA, is exploring ways to increase the cost-effectiveness of spacecraft by reducing the weight and size of payloads.

[16] See U.S. Congress, Office of Technology Assessment, *Civilian Space Policy and Applications* (Springfield, VA: National Technical Information Service, June 1982), for a description of the development of the Ariane and the role of ESA.

[17] Because it owns a substantial percentage of Arianespace stock, the French government has significant influence over decisions made by Arianespace.

[18] The typical Ariane 3 launch requires about 35 full-time launch personnel, plus additional personnel who assist in preparing the vehicle. The Ariane 3 typically requires about 4 weeks to assemble, integrate, and test, and 2 weeks on the pad. The Atlas-Centaur, which has approximately the same payload capacity, takes about twice as long for the same procedures.

Figure 5-1.—ESA/Arianespace Relationship


ESA member states
ESA
ESA as customer
ESA as monitor
Arianespace
Other customers
CNES*
Ariane 1 develop
Ariane 2/3 develop
Ariane 4 develop
Ariane 1 production
Production Ariane 2/3/4
Launch operations
Marketing sales finance
First launch pad
Second launch pad

*Centre Nationale D'études Spatiales (the French Space Agency)
SOURCE: Arianespace.

and authority for development and that for operations. This institutional division gives each institution a base of power from which to work in arguing its technical case for reducing operations costs. **Because Arianespace competes in the international marketplace, it has strong commercial incentives to minimize these costs.**

In order to make such an arrangement function in reducing costs, the U.S. Government would have to purchase services rather than vehicles, provide a strong economic incentive to reduce costs, and limit Government oversight, provided the launch company proved its capacity to deliver payloads to orbit within schedule and budget. The launch company would also have to assume a major portion of the economic risk of launch failure.

Such a division of responsibility would have several advantages. First, launch costs would be more visible and comprehensible than they are within the current institutional structure. Second, because the launch company would focus on launching vehicles and payloads for its clients, rather than on vehicle or payload development, it would have a major stake in limiting the number and extent of vehicle modifications that would negatively affect its ability to launch on schedule. Third, because the launch operations company would also be encouraged to compete for launch services in the international market, it would have considerable incentive to lower launch operations costs. Finally, if the ALS or other launch development program succeeds in substantially reducing launch costs, the launch firm would likely have many more private sector and foreign customers for launches than can be foreseen under existing demand projections. In general, the institutional tension that such a division of authority and responsibility would create could enhance innovation and lower costs of production.

This institutional arrangement would be successful only if the technology used in the ALS were, and were perceived to be, well within the state of the art. If significant components of the ALS pushed the limits of technology, such an arrangement would likely to be considered too risky by both Government officials and private industry.

The arrangement would wrest much of the control the Air Force and NASA now exert over launch operations from these institutions. However, unlike earlier proposals for privatizing the Shuttle system, this policy option would not involve piloted launchers, and therefore would not encounter the objection that a private corporation should not have control over a symbol of U.S. technological prowess. In other words, this model does not seem appropriate for operation of piloted reusable research and development vehicles.

Existing Launch Systems

In the absence of a massive reorganization of the launch institutions in NASA and the Air Force, it may still be possible to focus increased attention on reducing the Government's costs of operations.

In order to assist NASA and the Air Force in reducing operations costs for current launch systems, Congress could direct these agencies to establish an operations division independent of their launch development responsibilities. In both agencies, these functions are mixed. Consequently, because budgets are also co-mingled, it is often difficult or impossible to determine what operations procedures really cost. Separating development activities from operations more clearly would allow the agencies and Congress to focus more effectively on the true extent of operations costs. Such an institutional change has the strong advantage that it would lead to relatively few disruptions of NASA's and Air Force's current organizational structure and procedures. However, it has the disadvantage that it would force only a limited cultural change within the agencies toward operating launchers on the basis of lowered costs. This option, if pursued by Congress, would require considerable congressional oversight to assure that the agencies carried out the will of Congress. It would only work if users were required to pay launch costs.

The proposed space station is another large project in which operations costs would constitute a significant proportion of life-cycle costs. Because of its concern over the cost and management of space station operations, the National Research Council recently urged a similar organizational structure for the U.S. space station program. It has suggested "an organizational entity, independent of the space station development hierarchy, with the ultimate responsibility for operating the space station."[19]

In any event, Congress may wish to direct the Agencies to develop a plan with the goal of giving launch operations and logistics managers a stronger voice in the design of launch vehicles. The OTA workshop on launch operations affirmed the importance of giving launch operations and logistics managers an early and influential role in the design of new launch vehicles. They should also be given greater control over the budget for operations. Most participants agreed that any design changes to current vehicles should be made with the principle of lower operations and maintenance costs as a foremost criterion.

FOREIGN COMPETITION IN LAUNCH VEHICLES

NASA, the Air Force, and commercial launch companies should examine launch operations in other countries. U.S. agencies and companies tend to suffer from the "not invented here" syndrome. As one OTA workshop participant put it, "we in the U.S. believe that we are the leaders in technology application, and we can go off and do it as well as or better than anyone else. Thus we are reluctant to look at other nations and learn from their approaches." However, launch organizations in other countries may have something to offer in reducing operational costs.

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[19] National Research Council, *Report of the Committee on the Space Station* (Washington, DC: National Academy Press, 1987), p. 34.

For example, Arianespace, the commercial operator of the European Ariane launcher,[20] has focused its attention on reducing the costs of constructing and launching the Ariane, which unlike U.S. expendable launchers was originally designed as a launch vehicle not a missile. In designing the Ariane system, the European launch designers learned a tremendous amount from previous U.S. experience and used it in their own designs.

Japan has made considerable progress in developing its HI and HII launch systems. Because Japan is likely to offer the latter commercially, it will also give considerable attention to launch operations costs, especially because Japan needs a second launch center located near the equator in order to reach geosynchronous orbit more efficiently.

The United States can expect future foreign launch concepts like the U.K. HOTOL, the German Saenger, or the Japanese Spaceplane to be directed in part at commercial sales. The HOTOL and the Saenger, especially, are being designed with careful attention to improving launch operations efficiencies.

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[20] The European Space Agency (ESA) developed the Ariane launcher in the late 1970s. After extensively testing the Ariane, in 1984, ESA turned over management of launch operations to Arianespace, a French corporation supported in part by the French government.

Appendixes

Appendix A

Cost-Estimating Relationships

This appendix contains a brief summary of current cost estimation methods to illustrate the uncertainty and subjectivity involved. Methods used in the Space Transportation Architecture Study (STAS) are typical and are used as examples for the general discussion. The second half of this appendix presents three examples from STAS. One illustrates the derivation of a cost-estimating relationship for vehicle structures;[1] the other two illustrate estimated labor cost savings achievable by developing and applying automation technology.

A Summary of Cost Estimating Relationships Used in STAS

Ground Rules and Assumptions

A cost estimation effort such as undertaken in STAS must begin by making basic assumptions; those made by the sponsor of the analysis are included in stated ground rules, which also specify what the system must do. For example, STAS specified a matrix of possible mission models and required: 1) design and cost estimates of a minimum of two independent vehicles, with no major subsystems in common, including launch, orbital transfer, and return of specific high-priority payloads "to provide assured access"; and 2) design of facilities and equipment allowing a surge factor of 40 percent over the nominal launch rate.

Parametric Cost Estimation: When, as in STAS, systems are to be designed for economy, designers do not know optimal values of system parameters such as size and weight at the outset. The costs of vehicles or vehicle subsystems are therefore estimated parametrically; in other words, they are expressed as formulas called cost-estimating relationships, or CERs, which may be used to calculate estimated cost in terms of parameters such as weight.

A CER for a vehicle may be derived in a "bottom-up" manner by designing several launch vehicles that are similar except in size, and, for each vehicle, adding up the estimated costs of the subsystems and labor required. The costs of the subsystems may be estimated in a similar manner by designing them and adding up the estimated costs of the parts and labor required to build them, etc. This approach is labor-intensive, because it requires preliminary design of a vehicle.

Alternatively, a CER may be derived by fitting a curve to a "scatter plot" of the weights and inflation-adjusted costs of similar vehicles that have actually been built.[2] The most common procedure is a combination of these approaches: designers develop a preliminary design for a vehicle in only enough detail to estimate the weights of its major subsystems in terms of the vehicle weight or its payload capacity. CERs for the subsystems are then derived by extrapolation and interpolation from historic data, if they are available.

Individual CERs are derived for development costs and for the cost of producing the first unit. Incremental costs of additional units are assumed to be lower than the cost of producing the first unit by a factor that depends upon the number of units produced (learning effect) and the production rate (rate effect). CERs for labor costs of ground operations are derived in a similar manner.

Manifesting and Optimization

After CERs for vehicles, facilities, and operations have been developed, manifesting and optimization programs are employed to determine the most economical types and sizes of vehicles for the mission model. First, a trial mix of vehicles is assumed. A size is assumed for each vehicle, and its cost is estimated from the CERs. Then a manifesting program is run to determine the least costly way of combining (co-manifesting) payloads on vehicles so they reach their operational orbits in the specified year, taking into account any restrictions on co-manifesting for security and safety. The launch rates in the resulting manifest determine the operations costs, and the maximum launch rate, inflated by 40 percent to provide a surge capability, determines the number of facilities required for processing and launch. Costs of development, facilities, vehicle production, and operations are discounted and totalled to obtain a projected present value of life-cycle cost. The process is repeated assuming different vehicle mixes, sizes, and technologies, and different ground operations and mission control technologies, to determine the most economic architecture and technology content.

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[1] In STAS, costs of expendable hardware and spare reusable hardware are included in operations costs.

[2] For a comprehensive published description of this approach, see D.E. Koelle, "Cost Model for Space Transportation Systems Development, Fabrication and Operations" (Ottobrunn, FRG: Messerschmitt-Boelkow-Blohm GmbH, Bericht Nr. TN-RX1-328 B, 1983).

Estimation of Risk of Greater-Than-Expected Cost

STAS contractors estimated cost risk subjectively at the level of the vehicle systems mix, not in a bottom-up manner. The estimated risk, expressed as a cost, was given a 5 percent weight in the overall score used to screen system mixes, as specified by study ground rules. Those who estimated the risk may have been unfamiliar with cost risks apparent to subsystem experts. Moreover, cost risk was estimated *assuming* ground rules were met; risk that ground rules will not be met increases cost risk.

Cost Estimation Examples

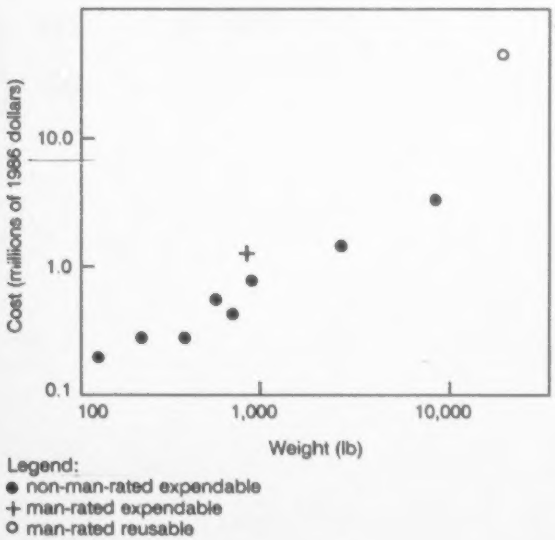
Example 1: Parametric Estimation of Vehicle Structure Cost

To derive a CER for the cost of vehicle structures (e.g., inter-stage adapters), one contractor began by plotting the weights and inflation-adjusted costs of vehicle structures it had built previously.[3] The resulting scatter plot is shown in figure A-1.

The contractor observed that the costs of the structures rated for human use—especially the reusable one, were significantly higher in proportion to their weights than were the costs of the expendable structures not rated for humans. It therefore decided to derive a basic CER for unpiloted expendable structures and *assume* that the greater costs of crew-rating and reusability could be represented by "complexity factors" by which the basic cost should be multiplied. The basic CER is represented by a straight solid line in figure A-1, and complexity factors for crew-rating and reusability are represented by arrows from this line up to the data points for the crew-rated systems. Figure A-2 was derived from three assumptions: 1) that design for reusability increases cost by a factor independent of structure weight, or 2) rating for human use, and 3) that the complexity factor for rating for human use is independent of structure weight.

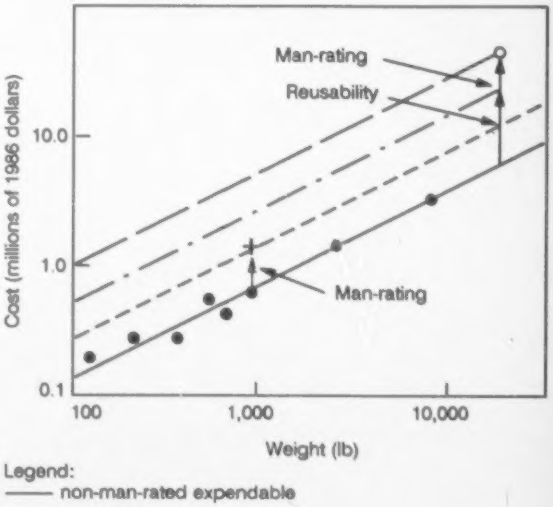
Critique: The contractor could verify assumption (3) by comparison with a commercially available CER, presumably derived from different data and independent assumptions; the contractor found good agreement, but this does not imply that the assumption would be correct in all cases. Assumptions 1 and 2 were neither supported nor contradicted by the limited data available to the contractor; they are educated guesses—the best the contractor could do under the circumstances. Although they are not clearly incorrect, their accuracy is unknown, and the contractor pre-

Figure A-1.—Historical Costs and Weights of Vehicle Structures



SOURCE: Office of Technology Assessment, 1988.

Figure A-2.—Cost-Estimating Relationships (CERs) for Vehicle Structures (first-unit production costs)



SOURCE: Office of Technology Assessment, 1988.

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[3] Such data are often proprietary, which makes valid comparisons with CER's derived by other manufacturers very difficult.

sented no estimates of uncertainty in the complexity factors. If the contractor or a Government agency had access to proprietary data of other contractors on expendable structures rated for humans, there might be enough data points to test assumptions 1 and 2, although the variety of vehicles built to date may be inadequate to accept or reject the assumptions with high confidence.

Example 2: Savings From Automating Ground Operations

This example and example 3 summarize the procedures a different STAS contractor employed to estimate potential savings from automating ground operations and mission control functions.

To estimate savings from automating ground operations, the contractor first calculated the labor required to perform functions such as refurbishing avionics using current methods based on estimates of labor required to perform similar functions on existing vehicles, and adjusted to reflect the fact that a new vehicle would have different needs. For example, a flyback booster would require a more robust thermal protection system than the Shuttle orbiter and would not require refurbishment. A percentage reduction in labor for each such function was then estimated for each new technology proposed (e.g., automated test & inspection). This reduction was assumed to be achieved by decreasing the crew size and the number of shifts by equal percentages; the reduction in processing time (number of shifts) allowed the required number of vehicles per year to be processed with fewer facilities, thus saving costs and lead time as well as direct labor costs for new facilities. From these savings was subtracted the costs of developing the new technology required and applying it; these costs "were estimated based on the costs associated with similar programs, including the costs of developing the STS Launch Processing System."

Critique: The relevance of such costs as a basis for extrapolation could be questioned, because comparable automation was not developed for the STS Launch Processing System.

Example 3: Savings From Automating Mission Control

To estimate savings from automating mission control, the contractor first estimated the recurring and non-recurring costs of performing five mission control functions (flight planning, simulation and training, payload integration, data load preparation, and flight control) using current technology. The costs of performing these functions in 1995, using 1990 technology, and in 2000, using 1995 technology, were also estimated; in general, the recurring costs were lower while the non-recurring costs were higher. At the high launch rates assumed, the life-cycle costs were lowered by assuming use of the new technology, when available. The fractions of net savings (cost reduction minus cost of technology development) for each function attributable to each new technology and to improved management were then allocated according to a formula, e.g., 40 percent of net savings on flight planning was attributed to use of expert systems. Technology development funding requirements were listed by year, although the contractor's reports do not make clear the basis for their derivation.

Critique: The costs of developing "ordinary" software have proven difficult to estimate accurately, even a posteriori, when the size of the program (on which some estimates are based) is known.[4] The accuracy with which existing methods can estimate costs of developing software such as expert systems is not known.

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[4] Chris F. Kemerer, "An Empirical Validation of Software Cost Estimation Models," *Communications of the Association for Computing Machinery*, vol. 30, No. 5, May 1987, pp. 416-429.

Appendix B

Noneconomic Criteria

Capacity of a space transportation system can be described in terms of maximum annual launch rate or payload tonnage. However, capacity is actually multifaceted and is better described by a set of numbers: the maximum launch rate of each fleet[1] to each of several reference orbits, along with trade-offs among these, if any (e.g., sharing of launch pads by different fleets).[2]

Flexibility is the "ability of the space transportation system to . . . respond to schedule, payload, and situation changes with . . . responsiveness . . . [and] capacity,"[3] " . . . and to satisfy missions in more than one way."[4] For example, a fleet's ability to share traffic (carry some or all payloads manifested for a different fleet) improves the flexibility of a multi-fleet system. Flexibility may be valued for its own sake or indirectly, if it contributes to resiliency, operational availability, or access probability.

Reliability is the probability with which a system will perform an intended function. A system designed to perform several distinct functions will have a reliability corresponding to each function. For example, a fully reusable vehicle would be designed to transport payloads to orbit safely *and* return safely. The probability that it will reach orbit and safely deploy a payload (its ascent reliability) is greater than its mission success reliability—the probability that it will reach orbit, safely deploy a payload, and return. Mission success reliability is a commonly used criterion, but reliabilities of non-critical subsystems are also of interest because they affect maintenance costs.

High reliability contributes to, but is not required for, resiliency and operational availability; it is necessary for high probability of access and return. Ascent and return reliabilities determine the risks of loss of payloads and reusable vehicle components; these risks include expected replacement costs as well as nonfinancial risks, e.g., to national security or political support of space programs. One of the difficulties in using reliability as a criterion is the uncertainty in estimates of the reliabilities of operational vehicles and, especially, proposed vehicles.

Because perfect reliability is unattainable, the marginal *cost of reliability* must increase without bound as reliability approaches 1.0, and a lower reliability must be optimal (see figure 2-4 in chapter 2). The optimal reliability would be the reliability at which the value of reliability less the cost of achieving that reliability is greatest. The value of reliability has been estimated in some cases by calculating the expected replacement costs of payloads and reusable vehicle components; such estimates have been used to argue, e.g., that reusable systems with reliability below .985 should not be considered as viable candidates. However, such estimates are likely to undervalue reliability because they neglect intangible risks. The costs of providing various reliabilities have been estimated by considering different configurations of critical components (e.g., engines) with different degrees of redundancy, totalling component costs, and estimating reliability from estimates of component reliabilities.

Resiliency is the ability of a space transportation system to adhere to launch schedules despite failures—to "spring back" after failure. A **fleet** is considered to be resilient if the probability of a failure while recovering from a failure is less than 0.35.[5] This criterion is derived from several assumptions:

1. Payloads are launched at a nominal launch rate until a failure occurs.
2. After a failure, launch attempts cease for a duration called the downtime, during which the cause of the failure would be investigated and corrected; however, the reliability of the launch vehicle is assumed to remain the same.
3. Reservations for some payloads scheduled to be launched during the standdown are assumed to be canceled; the rest, a fraction called the backlog factor, are added to the pre-failure backlog (if any) of payloads queued for launch.
4. When launches resume, payloads are launched at the maximum launch rate (the surge rate) at which the system can operate in an effort to reduce the backlog. Meanwhile, new payloads are readied for launch at the nominal launch rate and are added to the backlog.
5. Launches continue at the surge launch rate until the backlog is eliminated, unless another failure occurs first.

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[1] A fleet is that portion of a space transportation system which consists of launch vehicles of a single type, e.g., the Shuttle fleet, the Titan-IV fleet, etc.

[2] Capacity was not used as a screening criterion in STAS because candidate architectures were required to have sufficient capacity to fly all missions in the mission model. Excess capacity contributed to architecture scores indirectly through effects on operational flexibility and resiliency, etc.

[3] Joint Task Team, *National Space Transportation and Support Study 1995-2010,* Annex E ("DoD Functional/Operational Requirements"), May 1986, p. 5.

[4] Ibid., Annex C, p. 12, tab. 2-3.

[5] The resiliency of each fleet of a multi-fleet space transportation system may be calculated as though it were the only fleet, if no fleet can carry payloads manifested for a different fleet. The resiliency of the multi-fleet system is considered inadequate if the resiliency of any of its fleets is inadequate. If the fleets can share payloads, calculation of the probability of a failure during a surge period can be very complicated.

If the probability of a failure during a surge period exceeds 0.35, it is unlikely that the backlog can ever be eliminated after a first failure.[6] However, resiliency may be made as good as desired by changing any one (or any combination) of three of the four parameters that determine fleet resiliency: reliability, downtime, and nominal launch rate. Increasing surge launch rate results in only limited improvement in resiliency.[7]

Operational Availability is the probability that a fleet, or a multi-fleet system, will be operating (i.e., not standing down) at a randomly selected time.[8] Operational availability is intimately related to resiliency; a fleet or system with high resiliency will have a high operational availability. Reducing downtime can make operational availability as great as desired; a fleet that never stands down is always available, even if unreliable. A mixed fleet is not required for high operational availability.

Access Probability is the probability that a space transportation system can launch a payload *and* that the payload will reach its operational orbit intact. Two kinds of access probability can be distinguished: probability of access on demand, and probability of access on schedule. High probability of access on demand requires flexibility—so that a high-priority launch can be scheduled quickly when required for national security—and high probability of access on schedule, so that the scheduled launch will most likely be successful. Probability of access on schedule is operational availability (the probability that a launch can be attempted when scheduled) times vehicle reliability (the probability that the payload will reach its intended orbit intact if launched).[9] [10]

A space transportation system is often said to provide *assured access* if it provides means for placing high-priority payloads in their operational orbits on demand with high probability. Access probability depends on the payload—and the variety of vehicles that can launch it—and is more important for some payloads than for others.

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[6] Harry Bernstein & A. Dwight Abbott, "Space Transportation Architecture Resiliency," (El Segundo, CA: The Aerospace Corp., March 1987).

[7] The probability of a failure during a surge period (P_F) may be calculated from the formula

$$P_F = 1 - P_s^{T_d K(T_d) SR_n/(S-1)}$$

where P_s is the launch vehicle reliability, R_n is the nominal launch rate, SR_n is the surge launch rate, S is the surge factor (SR_n/R_n), T_d is the downtime, and $K(T_d)$ is the backlog factor, which depends on the downtime. Downtime is defined as the interval from a failure until the next operational launch attempt. $K(T_d) = 1 - T_d/6$ is assumed.

[8] This does not mean that it must always have an unreserved vehicle on a pad ready to launch on a day's notice.

[9] N.b.: traffic sharing is not required. Cf. STAS groundrule A-1: "Viable architecture will be based on a mixed fleet concept for operational flexibility. As a minimum, two independent (different major subsystems) launch, upper stage, and return to Earth (especially for manned missions) systems must be employed to provide assured access for the specific, high priority payloads designated in the mission model."

[10] If downtime has not been minimized, traffic sharing may improve access probability, otherwise it can reduce it. If a reliable launch vehicle fails, using a backup vehicle that is less reliable than the primary launch vehicle payload will decrease the probability of getting the shared payloads to orbit safely. If the primary vehicle were indeed more reliable, it would be safer to use it while accident investigation proceeds; its unreliability, even if due to systematic problems, would be lower. Moreover, it would be costly to maintain a backup fleet.

Appendix C

Reliability

Launch vehicles can in principle be made very reliable by incorporating redundant components and subsystems, and by detailed testing during manufacturing and launch operations. However, it is costly to manufacture a highly reliable vehicle, and maintaining and verifying its reliability until launch imposes heavy burdens, high costs, and delays on ground operations. Yet, operating a fleet of unreliable vehicles is also costly: direct financial costs may include the replacement costs of payloads and vehicles and the costs of supporting the launch operations force during a standdown.

If only financial costs are considered, it is possible to determine the most economical reliability for a vehicle, if payload replacement costs, etc., can be estimated before the vehicle is designed. This has been done for some launch vehicles and orbital transfer vehicles.[1] Intangible costs may also be included if expressed in monetary terms. However, this requires subjective judgement of the value of military satellites to national security,[2] and other intangibles.

The reliabilities of currently operational launch vehicles are not known with certainty or precision. On the basis of actual launch experience, they can only be said to lie within certain confidence intervals with corresponding statistical confidence. As more launches are attempted, the confidence intervals will shrink and statistical confidence will grow. The reliability of a proposed launch vehicle or variant can only be hypothesized on a semi-analytical, semi-subjective basis. Confidence levels for the reliabilities of currently operational launch vehicles are listed in table C-1.[3]

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[1] Boeing Aerospace Corp. has developed a computer program called STROP to perform such an analysis; it was first used to determine the most economical reliability for the Inertial Upper Stage.

[2] U.S. Congress, Office of Technology Assessment, *Anti-Satellite Weapons, Countermeasures, and Arms Control*, OTA-ISC-281 (Washington, DC: U.S. Government Printing Office, September 1985), p. 33.

[3] Confidence intervals are estimated from statistics in Harry Bernstein and A. Dwight Abbott, "Space Transportation Architecture Resiliency," (El Segundo, CA: The Aerospace Corp., March 1987), using the exact confidence bounds of Y. Fujino, *Biometrika*, vol. 67, 1980, pp. 677-681.

Table C-1.—Launch Success Statistics (since 1976)

Vehicle	Successes /attempts	Average success rate	Minimum reliability at equal confidence
Delta	60/63	95.2%	90%
Atlas E	25/28	89.3%	81%
Atlas/Centaur	26/29	89.7%	81%
Scout	14/14	100.0%	87%
Titan	51/54	94.4%	88%
Shuttle	24/25	96.0%	87%
Ariane	14/18	77.8%	69%

NOTE: Forecasts (for which OTA does not vouch) of the reliabilities of proposed vehicles differ, e.g.:
STS-1 (post-*Challenger*): 0.98 [Aerospace Corp.], 0.997 [GD], 1.0 [NASA HQ].
Titan-IV: 0.96 [Aerospace Corp.], 0.98 [GD].
MLV (Delta derivative): 0.96 [Aerospace Corp.], 0.978 [GD].

SOURCE: Office of Technology Assessment, 1988.

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